

# Disclaimer

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The development of a guide to assess nonpoint source pollution of surface water resources in South Africa

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### **EXECUTIVE SUMMARY**

### 1 Background

South Africa's National Water Act now, for the first time, outlines specific measures to control nonpoint sources of pollution. However, implementation of the National Water Act will be constrained by a lack of both human and financial resources. The benefits of the new legislation can, therefore, only be realised if we are able to focus our limited resources to best effect.

The primary goal of this project was to develop a Nonpoint Sources Assessment Guide that would assist water quality modellers and managers in selecting the most appropriate modelling tools for a range of nonpoint source assessment needs. This would focus the efforts of both managers and modellers, and would ensure that our limited resources are used optimally.

This project was conceived in three phases.

Phase 1:- A Situation Assessment of nonpoint sources in South Africa.

Phase 2:- The illustration of different nonpoint source assessment techniques using case studies.

Phase 3:- The Nonpoint Sources Assessment Guide.

This report details Phase 2 of the project.

# 2 Objectives

This report presents case studies that both describe nonpoint source assessment techniques in practice, and illustrate the use of the Guide. The primary objectives of this report are therefore to:-

- > Present case studies that demonstrate the links between the different nonpoint source assessment techniques and management needs.
- > Demonstrate the different approaches toward nonpoint source assessment in a range of catchments.
- Provide an illustrative link between nonpoint source assessment techniques and the Nonpoint Source Assessment Guide.

### 3 Linking nonpoint source assessments and management needs

Water quality management information needs with respect to nonpoint source assessment include;

- screening and scoping to identify potential nonpoint source contamination areas,
- · evaluation to compare relative nonpoint source contributions from different areas,
- prioritisation to identify the most significant nonpoint source loads, and
- selection to identify the likely effects of nonpoint source management practices.

Nonpoint source assessment techniques disaggregate or lump nonpoint source processes in different ways. They may also lump parameters spatially or temporally. This largely determines their value to meet these management needs. These considerations are illustrated using several case studies from South African catchments.

### 4 Qualitative nonpoint source models

A GIS based model was developed by the Institute for Water Quality Studies to identify sediment production areas in the Olifants catchment. The model is based on an expert system or heuristic

approach, where sediment production potential is estimated from qualitative assessments of the factors that lead to soil erosion. As the input data are available in spatial format, the model is easily adapted to the GIS platform, and produces maps of potential sediment production.

The heuristic and spatially disaggregated nature of the model makes it flexible, and it can be readily adapted to answer specific management needs. The technique is therefore particularly suited to a screening and scoping level of assessment, but as it does not provide quantitative data its value to compare loads from different land use types or catchments is limited. The model also does not model sediment production and delivery mechanisms in detail, and has no temporal scale. As such the model can not be used for simulating the likely effects of nonpoint source management practices.

### 5 Simple statistical and deterministic models

Simple deterministic and statistical models are based on the relationship between stream flow and pollutant concentrations to calculate pollutant loads. Statistical models determine the empirical relationship between stream flow and pollutant concentrations, and use this relationship, together with simulated or observed stream flow to simulate total pollutant loads. It is possible to estimate the nonpoint source component of this load by separating base and storm flows, or from catchment characteristics. Simple deterministic models use observed or simulated stream flow sequences as the basic input variable, but associate pollutant loads with processes that lead to nonpoint source pollution.

These models provide quantitative assessments of nonpoint source contributions from different geographic areas, and they support an evaluation assessment of management needs. However, these models lump land use types and nonpoint source processes. While this makes them easier to calibrate, it limits their value as tools to predict the impacts of management practices, or to assess the relative loads from different land use activities. They are consequently most suited to catchments where the lumped parameter problem is not an issue (eg. catchments that are dominated by a single land use type) or where managers do not need to identify specific management practices. These models must also be calibrated, which means that stream flow data and concentration data must be available.

### 6 Models which disaggregate catchment processes and land uses

The Catchment Washoff Model dissaggregates catchment processes and land use. The model is consequently a closer representation of catchment nonpoint source processes. As the model disaggregates landuse, it allows the user to assess the relative nonpoint source loads from a number of different land use types.

The model consequently supports a prioritisation level of management needs, especially where several land use types may contribute to the observed problems. The model does not, however, model the detailed nonpoint source production and delivery processes on each land use type, and can not be used to assess the effects of nonpoint source management practices. As such the model can not support the selection of management practices.

### 7 Models that detail the nonpoint source processes

A detailed case study of nonpoint sources of *E coli* in the Camps Drift catchment represents a highly dissaggregated model. This model is based on a detailed understanding of the main processes governing faecal contamination of water bodies in a peri-urban catchment, and disaggregates these

processes as much as possible. This allows managers to identify the actual causes of the problem and to develop detailed management practices to address these causes.

By separating the production, delivery and transport processes, the model also allows managers to focus limited resources on the most cost-effective solutions, and to identify those production areas, and delivery mechanisms contributing most to the observed water quality problems. As such the model primarily supports the selection of appropriate management practices. However, this type of model requires a detailed understanding of the processes causing pollution, and detailed calibration data. As such it is costly to calibrate, particularly on larger catchments.

### 8 Conclusions

Nonpoint source models aggregate or disaggregate the processes that lead to pollution in different ways. Similarly, different models may aggregate or disaggregate land use types (spatial resolution), or may have different temporal resolutions. This largely affects their use for different management needs.

However, more disaggregated models, while providing for a greater range of management needs, are more time consuming to calibrate and may be restricted smaller catchments. Water quality managers and modellers should, therefore, carefully match the model capabilities with their respective needs.

## 1 THE PROJECT CONTEXT

### G Quibell

# 1.1 Background

Although the first national legislative provisions to protect South Africa's water resources were included in the Union Health Act of 1919, water quality management primarily originates from the Water Act of 1956 (Act 54 of 1956). This Act required water users to discharge effluent back to the water resource from which it was originally abstracted. However, recognising the impacts these effluents may have on downstream users, this Water Act also specified that effluent had to comply with certain quality requirements. The 1956 Water Act, therefore, only addressed *point source* discharges. For many years these point source controls remained the cornerstones of water quality management in South Africa.

In the 1980's water quality managers became increasingly aware that deterioration in the quality of the water resource was not only caused by point sources, but that certain land use activities resulted in significant nonpoint source pollution problems. This led to the promulgation of the Water Amendment Act (Act 96 of 1984). This Act allowed water quality managers to regulate any activity that could render the water resource less fit for use. This allowed for nonpoint source management on a site-specific basis. However, during the 1980's water quality management in South Africa remained largely focused on point source control.

The publication of the White Paper "A National Water Policy for South Africa" in April 1997, for the first time outlined specific provisions for managing land use activities as nonpoint sources of pollution. The National Water Act (Act 36 of 1998), which represents the culmination of the Water Law Review process, specifically makes provision for the management of nonpoint sources within an Integrated Catchment Management (ICM) approach. This Act allows for managing the effects of nonpoint sources by identifying appropriate standards and management practices for different land uses either on a site specific basis, or generically to address nonpoint sources on a national or catchment basis.

The evolution of South Africa's Water Law has, therefore, increasingly provided water quality managers with the policies and the legal tools required to manage both point and nonpoint sources of pollution. However, implementation of the National Water Act will be constrained by a lack of both human and financial resources. Clearly, the benefits of the new legislation can only be realised if we are also able to focus our limited resources to best effect.

It was within this context, and with the recognition that approaches toward nonpoint source management had lagged somewhat behind those for point source management, that the Water Research Commission initiated a project aimed at developing a guide for nonpoint source assessment in South Africa. The aims of this project were as follows;

- Describe the "state of the art" with respect to nonpoint assessment in South Africa and the rest of the world,
- Outline the most important nonpoint source problems in South Africa,
- · Undertake nonpoint source assessment studies in a few pilot catchments, and
- Produce a Nonpoint Source Assessment Guide to identify appropriate nonpoint source assessment tools to assist water quality managers when managing these sources.

# 1.2 The Approach Used

<sup>&</sup>lt;sup>1</sup> A Nonpoint Source Assessment is defined as an investigation into the contribution that nonpoint sources make to an observed water quality problem.

The primary aim of the project was to provide water quality managers with a guide to identify appropriate nonpoint source assessment (modelling) tools. However, it was also recognised that the guide had to be backed up by studies which demonstrated the contribution nonpoint source assessment could make to managing water quality on a catchment basis. The project was therefore conceived in the three phases outlined below:

### Phase I

Aimed to produce a Situation Assessment of the current state of knowledge concerning the technical components of nonpoint source problems and assessment in South Africa, and its links to water quality management.

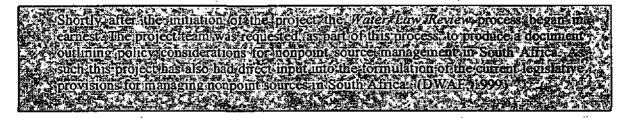
### Phase II

Aimed to conduct or evaluate a series of case studies to evaluate the application of nonpoint source assessment techniques for various problems in different parts of South Africa.

#### Phase III

Aimed to develop a guide for the quantification and assessment of nonpoint source contributions to water quality problems in South Africa.

This report represents the culmination of the second phase of the project.



# 1.3 The Objectives of this Report

The Situation Analysis report (completed under the first Phase of this project) indicated that, in general, there is a sound understanding of the causes of nonpoint source pollution in South Africa, and land use activities that contribute to these problems. Similarly, the water quality problems which typically originate from nonpoint sources are also recognised, and in many instances the assessment techniques (modelling tools) associated with nonpoint source problems are well known and have been tested locally. However, historically the management of nonpoint sources has been ham pered by:-

- inadequate legislation and regulatory authority.
- · poorly defined linkages between policies and implementable management practices, and
- undirected assessment of the nonpoint source problems in terms of management information needs.

As indicated above, recent developments have provided water quality managers with the legislative tools and regulatory authority to more effectively address nonpoint source pollution. Studies have also already been initiated to develop strategies and management practices to address specific nonpoint source problems associated with certain land uses. However, these initiatives will only realise their full potential if managers can focus limited resources on priority nonpoint sources. There is, consequently, a need to link nonpoint source assessment techniques both with the needs of water quality managers, and with water quality management policies.

The third Phase of this project was aimed at producing a Nonpoint Sources Guide, which would provide nonpoint source modellers and water quality managers with a tool to facilitate the choice of appropriate assessment techniques. This phase of the study would present case studies to illustrate the nonpoint source assessment techniques described in the Guide. The primary objectives of this report are therefore to:-

- > Present case studies that illustrate the links between the different nonpoint source assessment techniques and management needs.
- > Demonstrate the different approaches toward nonpoint source assessment in a range of catchments
- > Provide an illustrative link between nonpoint source assessment techniques and the Nonpoint Source Assessment Guide.

# 1.4 The Structure of this Report

This report aims to highlight the increasing levels of detail which may be required by water quality managers when addressing nonpoint sources of pollution, and has the following structure:-

### Chapter 2

Outlines the policy environment and management needs with respect to nonpoint source pollution in South Africa. This is used to illustrate the links between different management needs, and levels of nonpoint source assessment.

### Chapter 3

Outlines a qualitative GIS based tool for identifying nonpoint sources of sediment production in the Olifants River catchment. This tool supports a screening and scoping level<sup>2</sup> of management decision making, and addresses potential pollutant production.

### Chapter 4

Presents the simple statistical and deterministic models, which can be used for quantitative assessments of the total nonpoint source contributions. This tool is aimed at an evaluation level<sup>2</sup> of management needs, and simulates pollutant export from gauged catchments.

### Chapter 5

Presents the Catchment Washoff Model, and its use in the Amatole Systems Analysis. This assessment tool supports a prioritisation level<sup>2</sup> of management needs, and simulates pollutant yield from different land uses.

### Chapter 6

Presents a nonpoint source urban faecal contamination model, which was developed for the Camps Drift catchment. This supports a selection level<sup>2</sup> of management needs, and models pollutant production, delivery and transport.

### Chapter 7

Provides a summary and comparison of the various nonpoint source assessment tools, and how they support different management needs. The model attributes are highlighted, to further illustrate the Nonpoint Assessment Guide.

### 1.5 Reference

DWAF (1999). A framework for Implementing Nonpoint Source Management under the National Water Act. Department of Water Affairs and Forestry and Water Research Commission, DWAF Rep No. WQP 0.1, WRC Rep No. TT 115/99 Pretoria, RSA.

<sup>&</sup>lt;sup>2</sup> See Table 2.1 (page 6)

# 2 LINKING NONPOINT SOURCE ASSESSMENTS AND MANAGEMENT NEEDS

# G Quibell

### 2.1 Introduction

While there is a sound understanding of the extent and origins of nonpoint source pollution in South Africa, nonpoint source pollution has not been effectively addressed on an extensive scale in this country. Similarly, a wide range of nonpoint source assessment tools have been applied to a number of catchments in the country, but have not been systematically used to support management decision making. This has meant that limited management resources have not been effectively focused on those nonpoint sources that contribute most significantly to water quality problems. This suggests that researchers have not effectively identified management needs, and/or that managers have not selected appropriate assessment tools to address their needs<sup>3</sup>.

Changes in legislation now provide even greater challenges with respect to identifying priority nonpoint source problems within a catchment context. Consequently, there is an increasing need to link management requirements to nonpoint source assessment techniques. This chapter outlines management requirements with respect to current policies towards water resource protection. This provides a basis for identifying water quality management needs, and linking these to appropriate nonpoint source assessment techniques. The case studies in the following chapters refer to these needs, and provide illustrative examples of how nonpoint source assessment can support current approaches toward protection of the water resource.

# 2.2 Nonpoint source management needs required by the National Water Act.

### 2.2.1 Resource-directed measures

The White Paper "A National Water Policy for South Africa" (DWAF, 1997), and the National Water Act indicate that protection of the water resources of the country will be based on both Resource- and Source-directed controls.

Resource-directed measures aim to identify an appropriate level of protection for different water resources. This will be done within a Water Resources Classification system, and by setting the "Reserve" and "Resource Quality Objectives" (RQOs) for different water resources. Together these provide the basis of the water resource protection measures under the new Act. The Act indicates that all powers and duties performed in terms of the Act must give effect to these resource-directed measures. Furthermore, the classification system may also determine land use practices that will be prohibited near certain water resource classes.

The Resource-Directed measures, therefore, help determine:-

• The priorities for nonpoint source management (i.e. where areas which have a high nonpoint source potential occur near sensitive water resources)

<sup>&</sup>lt;sup>3</sup> These issues have been addressed in more detail in the Situation Analysis produced as part of Phase 1.

- Appropriate nonpoint source management practices for different receiving water resource classes, (i.e. where more stringent management practices are required to reduce the risks to sensitive water resources), and
- Whether nonpoint source management is effective (i.e. by identifying where nonpoint source pollution results in non-compliance to the RQOs).

### 2.2.2 Source-directed controls

While the resource-directed measures provide the framework for directing management resources, management of pollution from nonpoint sources will be effected by source-directed controls. These aim to establish management practices that are appropriate to manage both point and nonpoint source pollution. These standards may be set for specific sites or may be generic to certain land use types. Standards may also be implemented on a catchment basis or national basis.

Given the limited resources available to address water quality problems, nonpoint source assessment tools must therefore:-

- Prioritise nonpoint source types (land uses) for the development of management practices (i.e. by identifying those sources with the greatest contributions), and
- Assess the efficacy of management practices proposed for these controlled activities (i.e. by modelling the likely effect of certain management practices).

### 2.2.3 The Catchment Management Approach

The Department of Water Affairs and Forestry intends to manage water resources on a catchment basis. This process involves integration of water user's quantity and quality needs, and integration of land use and land use planning decisions with water quality management goals. This requires a holistic view of all pollution sources, and their relative impacts on water within the catchment as a whole.

Management of nonpoint sources in this context will have to be based on:-

- Identifying nonpoint sources of pollution in the catchment (i.e. where the nonpoint source problems areas are).
- Determining the relative contributions of these sources to water quality problems (i.e. which sources contribute most to the observed catchment water quality problems), and
- Determining the likely impacts of land use planning decisions on water quality (i.e. the likely impacts of new land use activities).
- Determining the likely effects of nonpoint source management on catchment water quality.

### 2.3 Different information needs

A number of nonpoint source assessment needs can be distilled from the requirements of the National Water Act as discussed above. These also represent an amalgamation of the stages of the Integrated Environmental Management (IEM) process (DEAT, 1992) and the theory of water resource systems planning and management (Loucks et al., 1981), and can be summarised as:

• The Situation Analysis Phase

- The Planning Phase
- The Implementation Phase (with iteration between the Phases)

Each of these requires a different type of nonpoint source assessment, and support different management needs (see Table 2.1).

Table 2.1. The management needs that are supported by different types of nonpoint source assessment.

Management Phase	Level of Assessment	Assessment Action => Management Decision
Situation Analysis	Screening/ Scoping	preliminary overview of the existence and extent of a problem => what are the nonpoint source areas?
	Evaluation	detailed investigation of the cause-and-effect relationships => what are the key nonpoint source areas and their relative importance?
Planning	Prioritisation	rank the problems and causes in terms of severity and manageability  => which nonpoint sources contribute most significantly to observed problems?
	Selection	estimate the cost effectiveness of possible actions => how effective will various management practices be?
Implementation	Operation	estimate the impacts of "real-time" actions => are management practices effective?
_	Auditing	monitor the degree to which conditions are meeting objectives => are more stringent practices necessary?

### 2.4 The Production, Delivery, Transport and Use continuum

Water quality management needs can also be identified by outlining the processes that lead to pollution. Managers can then assess which of these processes are manageable, and where in this continuum management would be most effective. The process of pollution can be conceptually broken down into a continuum in which pollutants are produced, are delivered to the water resource, are transported through the water resource, and finally where they affect the use of the water. These processes, and their links to water quality management needs, are discussed overleaf.

- Production refers to the generation of pollutants within certain land use types. This includes
  waste generated from human activities, as well as sediment production from erosion in the
  catchment. Minimising the production of pollutants equates to a philosophy of waste prevention,
  and this should be the preferred point at which to address pollution. Traditionally DWAF has not
  focused much management attention on minimising the production of waste.
- Delivery refers to the movement of these pollutants into the surface or groundwater
  environment. In the case of nonpoint sources this process is primarily hydro-meteorologically
  driven, but nonpoint sources may also include seepage of pollutants from irrigation or from
  poorly serviced densely populated areas. Minimising the amount of pollutant that can be
  mobilised into the water environment equates to a philosophy of waste minimisation. Similarly.

management practices aimed at trapping this waste before it is delivered to the water environment ensure *impact minimisation*. DWAF has concentrated most of its management attention on minimising the delivery of waste to the water environment, by setting effluent standards and management practices to trap and remove the waste before it reaches the water environment.

- Transport refers to the movement of waste once it has reached the water environment, as well as the chemical, physical and biological transformations that may occur in this process. Transport occurs through either the surface or groundwater component. The Receiving Water Quality Objectives approach was based on the assimilative capacity of the water environment i.e. on the Transport component.
- Use refers to the action of using the water. This also provides opportunities for management, for example by treating the water before use, or by warning communities not to use, or swim in, rivers and dams.

These processes have been described by Pegram et al, (1997), and the links between these processes and management philosophies have been described by Quibell et al, (1997)

The problem of pollution from nonpoint source pollution can be addressed at any point in this continuum. However, nonpoint assessment techniques model these processes differently. Some combine production and delivery into *yield*, while others combine production, delivery and transport into *catchment export*. This affects their use with respect to identifying management practices aimed specifically at either production or delivery, and hence whether they can support waste prevention or waste minimisation philosophies.

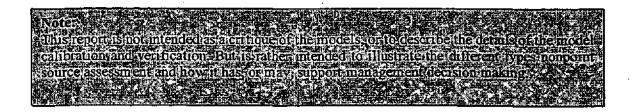
The case studies in the following chapters identify how this production, delivery and transport continuum is modelled by different nonpoint source assessment techniques, and the implications this has for selecting appropriate techniques. (Nonpoint source assessment techniques do not address the "Use" component of the continuum)

### 2.5 Linking management needs to nonpoint source assessments

The above discussion has indicated that different nonpoint source assessment techniques will be required to address a range of management information needs. These range from techniques that only provide qualitative assessments of potential pollutant production areas at the screening and scoping level, through to detailed quantitative assessments of the efficacy of various management practices aimed at delivery or production mechanisms.

The following chapters describe a number of models that are aimed at these different management needs. This is used to illustrate how different levels of nonpoint source assessment techniques support different management needs. The terminology used in this chapter to describe management needs is carried through the document to help identify which techniques support the management needs highlighted in this section.

The Nonpoint Source Assessment Guide (which has been produced as part of Phase 3 of the project, Pegram and Görgens, 2000) is intended to guide both managers and nonpoint source assessment protagonists in selecting appropriate assessment tools for their specific needs. The following chapters of this report therefore support the Guide, and serve to further illustrate the links between management needs and assessment techniques.



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# 3 A QUALITATIVE (GIS BASED) MODEL OF NONPOINT SOURCE AREAS (MODELLING SUSPENDED SEDIMENT IN THE OLIFANTS RIVER CATCHMENT)

### J Moolman, G Quibell and B Hohls

### 3.1 Introduction

In many cases the management practices required to address nonpoint sources of pollution are well known, but limited resources preclude their application on a national or even catchment wide basis. In these cases water quality managers need only identify potential nonpoint source problem areas, and their relative importance. This does not necessarily require detailed quantitative assessments of nonpoint source contributions, but simply the identification of problem areas. Sediment production is one such problem.

Sediment has long been recognised as one of South Africa's more important water quality problems, and management of erosion forms an important part of water quality management in many areas. The principles of sediment production are well documented, as are appropriate management practices to address the problem. In spite of this sediment remains a significant water quality problem in many areas, most likely due to the fact that limited resources are not focused on the most important sediment production areas.

Unfortunately, most methods of estimating sediment production, such as the Universal Soil Loss Equation (USLE), are focused on small catchments and require fine resolution data inputs. Data at this resolution are often not available for large areas and alternative methods are needed to identify potential problem areas over larger catchments.

A GIS-based approach was developed and tested in the Olifants River catchment to provide a rapid screening and scoping nonpoint source assessment tool. This tool provides the initial information required to focus management efforts within the catchment. The approach is based on qualitatively combining the factors that affect the potential availability of sediment (land cover and soil erodibility) with those that affect the potential washoff of this sediment (slope steepness, rainfall depth and rainfall erosivity). Sediment availability is then linked to washoff potential to identify areas of high, medium and low sediment production potential. Since sediment is a carrier of many of the microbiological indicators, nutrients and toxic materials, the method can be extended to identify and qualitatively rank source areas of these materials.

### 3.2 Description of the catchment

The Olifants River catchment (Figure 3.1) was chosen to test the method. It has a catchment area of 54570 km<sup>2</sup> extending from south of Witbank in Mpumalanga to Phalaborwa in the Northern Province. The rapid siltation of Phalaborwa Barrage requires frequent scouring, resulting in fish kills further downstream in the Kruger National Park. Irrigation farmers in the catchment have also complained of sediment damage to equipment and the deposit of sediment on plant leaves.

Suspended solids data are available for the Olifants River catchment (see Figure 3.2), and are generally better than most other catchments in South Africa. However, even in this catchment sampling has concentrated on certain areas and has not included all the sub-catchments. In addition, sampling frequency has been very low at some points. This makes it difficult to draw conclusions concerning the

origin of the sediment problems in the lower Olifants River from observed data. Similarly, there are very little data available to calibrate detailed sediment production models. This lends further support to the need to develop a rapid screening and scoping tool to identify nonpoint sources of sediment.

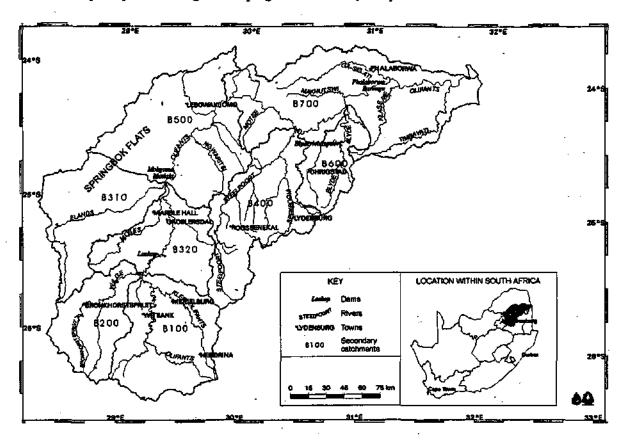


Figure 3.1 Physical description of the Olifants River catchment in South Africa

# 3.3 The procedure used to model sediment production areas

### 3.3.1 The factors affecting the production of sediment

The displacement of sediment by water depends on the amount and erosivity and the rainfall, slope of the terrain, soil erodibility, and the extent of ground cover. These factors can be further grouped into those that affect:-

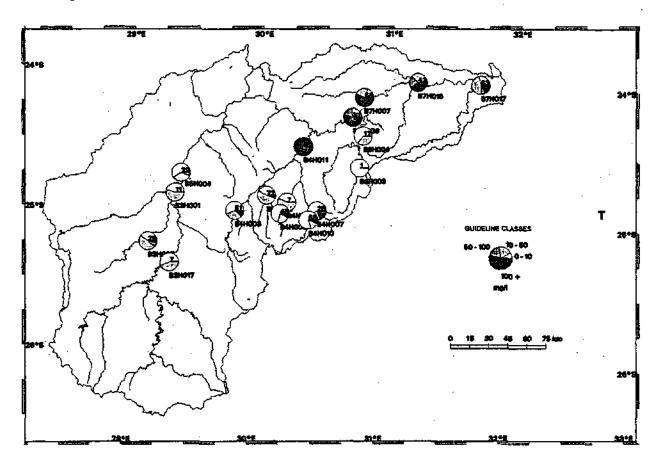
- 1. the availability of sediment (i.e. soil erosion hazard and land cover), and
- 2. the washoff of this sediment (i.e. rainfall erosivity, MAP and slopes).

("Washoff" and "Availability" are in fact common to all nonpoint source problems)

Qualitative assessments of these factors can be combined to identify areas of high, medium or low sediment availability and washoff potential. For example steep slopes, combined with high energy rainfall and a high MAP yield a high washoff potential, while erodible soils, poor ground cover and certain land uses yield a high sediment availability. High washoff potential together with high sediment availability in turn identify areas with a high sediment production potential. These factors are all spatial in character, making GIS the perfect platform to combine these data to produce sediment production potential maps. The following paragraphs describe the qualitative assessments used to classify the input data on this basis (Section 3.3.2). The spatial representation of these input data is presented in Section 3.3.3, while the combination of these to produce sediment production potential maps is presented in Section 3.3.4.

Figure 3.2: Pie symbols showing the frequency with which suspended solid guidelines are met at each point sampled in the Olifants River catchment (the number of suspended solid samples taken at each point is indicated in the centre of each circle.)

### 3.3.2 Data inputs



Soils

The erodibility of soils in South Africa was evaluated by the previous State Directorate of Agricultural Engineering and Water Supply (Lorentz and Schulze, 1995). These values are published as erosion hazard ratings for all the soil series in South Africa in Schulze (1995). Five erosion hazard classes were identified in these studies:

These five classes were reduced to three classes for this study, depicting low, medium and high soil erosion hazard, as follows:

Classes	Qualitative soil erosion hazard
1 – 2	(low)
3	(med)
4 – 5	(high)

### Land Cover

Land Cover data, based on Landsat Thematic Mapper satellite data are available for the whole of South Africa at 1:250000 scale<sup>4</sup>. These data provide the most suitable means of spatially identifying

<sup>&</sup>lt;sup>4</sup> These data are available from Environmentek (CSIR) and the Institute of Soil, Climate and Water (ARC – Agricultural Research Council).

the effects of land cover on sediment availability. This was done by assigning a value from 1 to 8 to each of the land use categories identified by the CSIR and ARC (Table 3.1). This was done based on expert opinion on the effects of land cover types on soil erosion. The 8 classes were further reduced for the Olifants River catchment to three qualitative classes as follows (Note: Other Erosion Potential classes could be used for other catchments)

Land cover Score	Qualitative erosion potential
1 - 2	1 (low)
3 5	2 (med)
6 - 8	3 (high)

### Rainfall Erosivity

The erosivity of rainfall can be described using the  $EI_{30}$  value. This is the product of the kinetic energy of a rainfall event and its maximum 30 minute intensity (Smithen and Schulze, 1982). Smithen and Schulze (1982) mapped average  $EI_{30}$  for South Africa, identifing nine  $EI_{30}$  zones in South Africa. Only zones 3 - 9 occur in the Olifants River catchment. These zones are divided into three classes for this catchment as follows (Other catchments may require other classes.)

EI30 zone	Qualitative rainfall energy class
3 - 5	1 (low)
5 - 7	2 (med)
7 - 9	3 (high)

Table 3.1 Ratings of land cover erosion potential

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Rainfall Amount

A map showing the distribution of mean annual precipitation (MAP) in South Africa is available as part of the 1996 Water Research Commission report on surface water resources of South Africa (Midgely et al, 1996). MAP for individual stations can also be obtained from the Computing Centre for Water Research (CCWR) and interpolation techniques used to derive the spatial distribution in an area. The Department of Water Affairs and Forestry (1986) identified the following three rainfall classes in South Africa:

MAP	Class
< 400 mm	1 (low)

400 - 800 mm	2 (med)
800 > mm	3 (high)

These classes were adopted for this study, however, other catchments in wetter or drier parts of the country may require other classes.

### Slopes

The Department of Land Information, Chief Directorate: Surveys and Mapping has a 400m x 400m resolution Digital Elevation Model (DEM) for the entire country. Elevations at a finer resolution of 200m x 200m, and even 50m x 50m, are available for some parts of South Africa. The 400m x 400m DEM was used to determine slope gradients (as a percentage) in the Olifants River catchment. These percentages were then divided into low, medium and high classes as follows:- (Other catchments may be classed differently)

Slope	Qualitative slope class
0 - 5	l (low)
5 - 25	2 (med)
25 - 161	3 (high)

### 3.3.3 Spatial data inputs for the Olifants catchment

Care was taken to ensure that all the input data were readily available in spatial data form for the whole of South Africa. As such the technique may be readily used on other catchments in the country. The qualitative classes may also be modified to suit local catchment conditions, to provide qualitative assessments of the main sediment production areas relative to that catchment. Similarly, default values may be used to determine sediment production potential relative to the whole country.

The spatial data for the Olifants catchment, after being qualitatively classed as above, were mapped to indicate areas of high, medium and low sediment availability and washoff potential using the methodology outlined in the following section. Figures 3.3-3.7 present the spatial data inputs used.

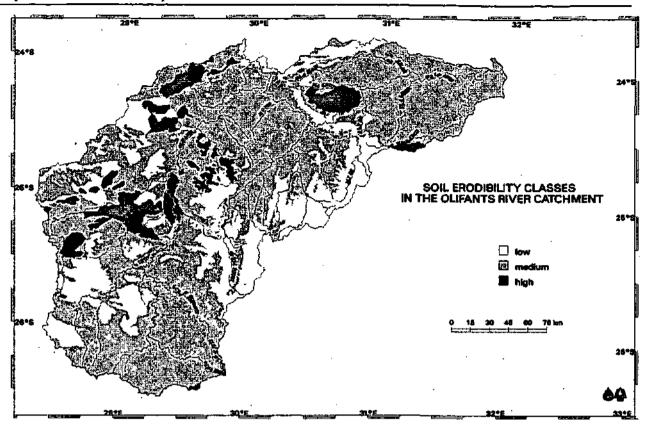


Figure 3.3 Areas of high, medium and low soil erodibility in the Olifants River catchment

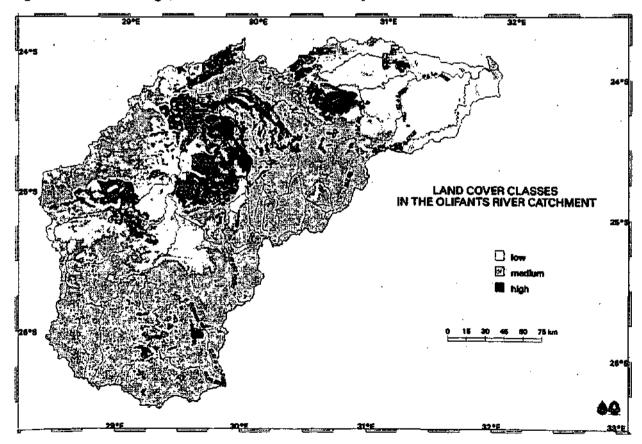


Figure 3.4 Land cover classes in the Olifants River catchment.

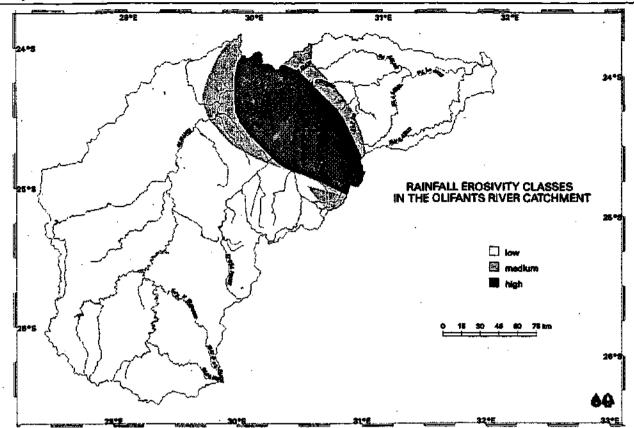


Figure 3.5 Areas of high, medium and low rainfall erosivity in the Olifants River catchment

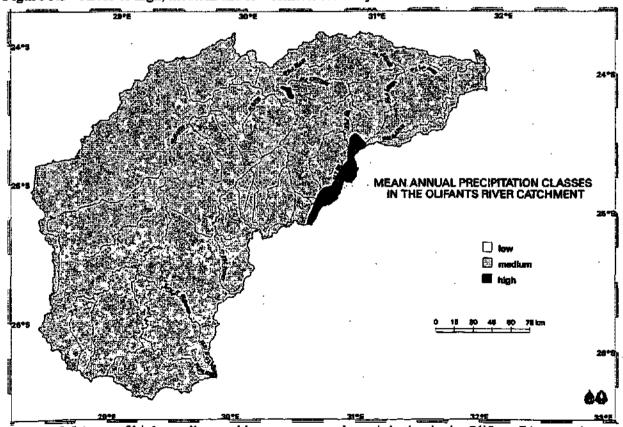


Figure 3.6 Areas of high, medium and low mean annual precipitation in the Olifants River catchment

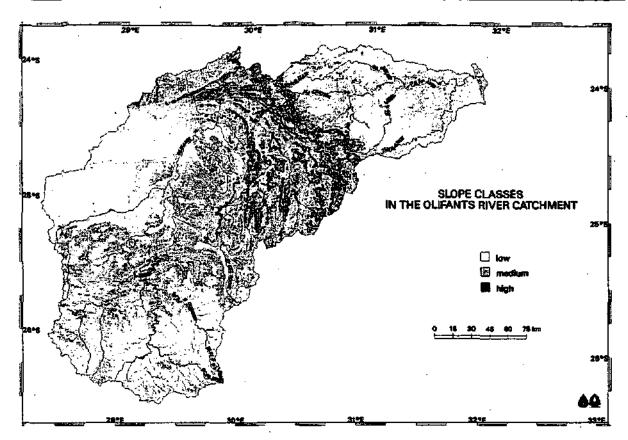


Figure 3.7 Areas of high, medium and low slope steepness in the Olifants River catchment

### 3.3.4 Combining the qualitative information in matrices

As indicated above, <u>sediment availability</u> depends on a) the type of soil and its erodibility potential, and b) the degree of land cover, while <u>sediment washoff</u> depends on a) the slope steepness, b) the rainfall erosivity, and c) the amount of rainfall. The qualitative classes identified above were therefore combined using the procedure outlined in Figure 3.8, and the matrices outlined in Tables 3.2-3.5.

Table 3.2 shows how the soils and land cover categories are combined to identify sediment availability, and Figure 3.9 presents the resultant sediment availability map.

Fable 3.2	Sediment availability matrix					
			SOILS			
·		1 (low)	2 (med)	3 (high)		
LANDCOVER	1 (low) 2 (med)	11.4 - 1. 2.72 - 2.7	2 章			
	3 (high)					

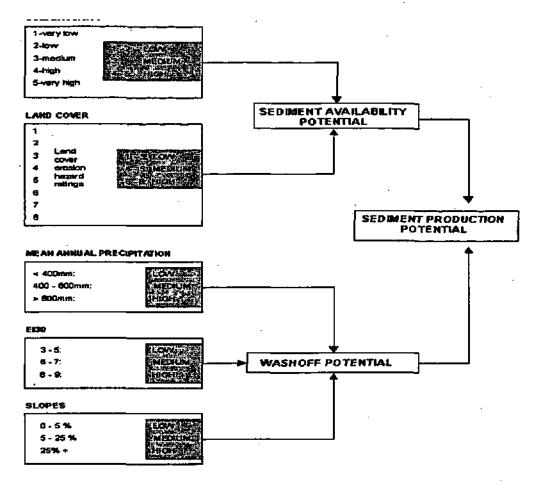


Figure 3.8 A diagram of the process used to combine the factors contributing to sediment production potential

Table 3.3 shows how the soils and land cover categories are combined to produce washoff potential categories, and Figure 3.10 presents the resultant washoff potential map.

Table 3.3 Washoff matrix										
	MAP	) - 	l(low)			2(med)		•	3(high)	
	EI30	1(low)	2(med)	3(high)	1(low)	2(med)	3(high)	l(low)	2(med)	3(high)
SLOPES	1(low) 2(med) 3(high)	10.00 200 3.000 3.000	2:	ical q egalar	2 3 5 6 7 - 1	(3.7.7. 		3 / . 6 5 C		

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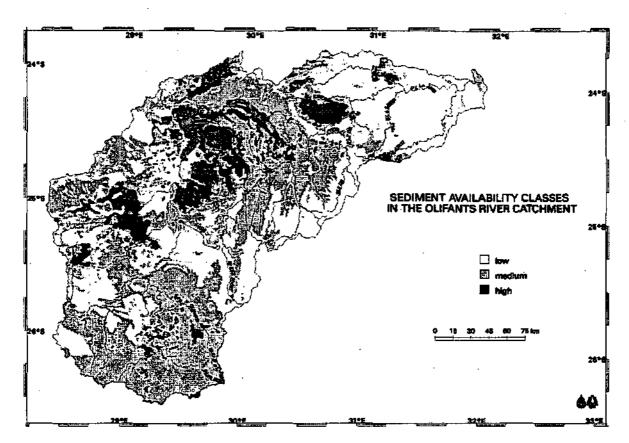
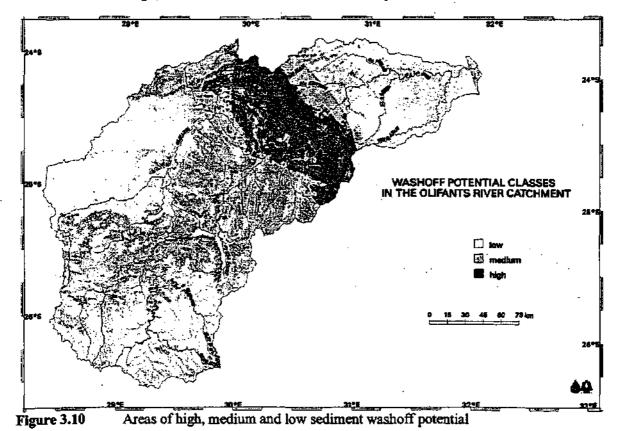
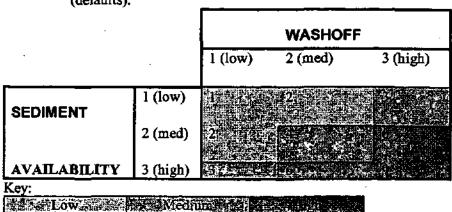


Figure 3.9 Areas of high, medium and low sediment availability in the Olifants River catchment



Sediment production potential can then be combined as indicated in Figure 3.8, using the matrix outlined in Table 3.4.

Table 3.4 Table of sediment production potential according to washoff and sediment availability (defaults):



However, given that the matrices are based on expert opinion, and are qualitative only, detailed knowledge of the nonpoint source problem and of the catchment in question can be used to refine the procedure. This was done for the Olifants catchment using the following assumptions:

- if washoff potential is high (eg. as a result of steep slopes), but sediment availability is low (eg. as a result of rocky areas), then the erosion potential will be low;
- if the washoff potential is low (eg. as a result of flat slopes), even if the sediment availability is high the overall erosion potential will remain low because the sediment removal is restricted.

These were used to refine the sediment production potential matrix as outlined in Table 3.5. Any other knowledge of the catchment or nonpoint source problem (for examples for areas where it is known that management practices have been implemented) can be similarly incorporated to focus the technique more on management issues.

The final map of potential sediment production areas in the Olifants Catchment, based on these refinements, is presented in Figure 3.11.

Table 3.5 Final potential Sediment Production classes

		WASHOFF		
•		l (low)	2 (med)	3 (high)
SEDIMENT	l (low)	Low	Low	Low Constitution
AVAILABILITY	2 (med)	Eow ₹ 19	Mell	WEE A
	3 (high)	Low	Water and	

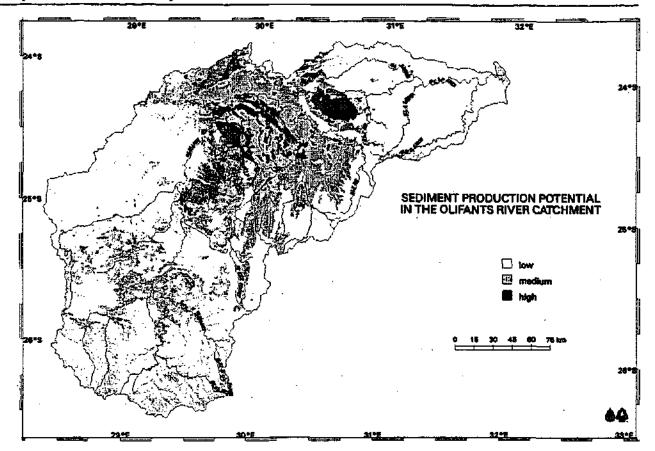


Figure 3.11 Final map showing areas of high, medium and low sediment production potential.

Figure 3.11 closely fits expert knowledge of the eroded areas in the catchment, as well as the sediment production areas that may be inferred from the suspended sediment data which are available. Most importantly it indicates that the densely populated areas, particularly in the lower Steelpoort and Makhutswi Catchments show the highest sediment production potential. The latter area is most likely the primary origin of the elevated suspended sediment concentrations noted in the Phalaborwa Barrage, and lower Olifants irrigation areas.

Examination of the various input maps also indicates that the sediment problem is mostly associated with the co-incidence of the most densely populated areas (and hence the most degraded veld) being associated with the steeper slopes and more intense rainfall. In the Makhutswi Catchment erodible soils appear to be the most important issue, whereas on the Sprinkbok flats, the impact of the erodible soils is mitigated by the shallow slopes. This would suggest that management attention should be first focused on the densely populated areas of the Makhutswi Catchment, and secondly on the Steelpoort valley. Care should also be taken to avoid further township development on the steeper slopes, particularly where erodible soils occur.

### 3.4 Using the technique for other nonpoint source problems

The concept of overlaying contributing factors to obtain an indication of potential risk can be extended to include other potential nonpoint source problems, using the same basic principle: The Potential for the nonpoint source problem is determined by the availability of the pollutant and the availability of water to wash it into nearby water resources (at least for surface water pollution). Since sediment also acts as a carrier of substances such as nutrients (phosphates and nitrates), a potential sediment production map can be combined with a map of land uses categorised according to their low (1), medium (2) or high (3) nutrient availability potential.

The effects of land cover on nutrient availability classification were based on the following generalisations:

- All cultivated land has a high nutrient availability.
- Stable natural vegetation (undisturbed natural vegetation, forest, woodland, thicket & bushland, unimproved grassland) has a low nutrient availability.
- "Forests & plantations" have a medium nutrient availability, due to greater disturbance with extended periods of minimal disturbance (unlike cultivated land).
- Wetlands and Waterbodies are classed as low as they act as nutrient sinks.
- Urban/Built-up land has a high nutrient availability, except where there is a significant portion of grassland (as on smallholdings) which are classed as medium.
- Improved grassland has a medium nutrient availability, because of the likelihood of fertiliser applications and other practices such as harvesting/cutting and grazing which will make nutrients more available.
- Degraded land is increased in value from the original cover class (low to medium, medium to high, etc.), with the exception of degraded unimproved grassland.
- Dongas and sheet erosion are rated as medium because of the uncertainty surrounding as to the adjacent landcover.

These principles were applied to the land cover map, which was then combined with the sediment production map to obtain a map of potential nutrient production (Figure 3.12).

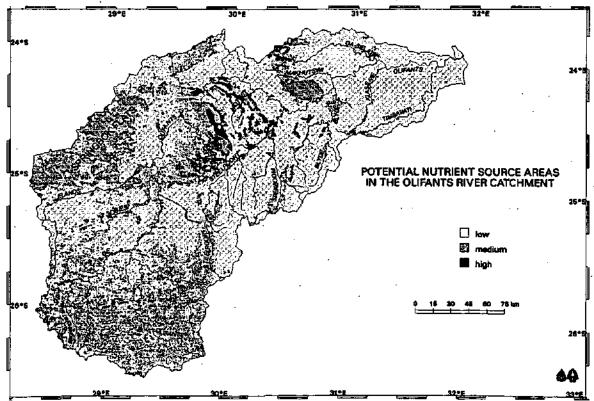


Figure 3.12 Final map showing areas of high, medium and low nutrient production potential

### 3.5 Conclusions

The method presented in this study uses readily available data to provide initial information at a screening/scoping level. It can be used by managers to quickly obtain an indication of the potential nonpoint source production areas in a catchment and expert knowledge of the nonpoint source problem

and of the catchment in question can be used to refine the final output. This makes the procedure very flexible, and it can be readily modified to suit a particular management issue. For example a land use which is not considered to be "manageable" (natural sheet erosion) can easily be assigned a zero class. In addition once on GIS the data can be readily further analysed to assess, for example, the land cover classes mostly responsible for the problems, or the sub-catchments with the greatest problems.

The management information produced by this procedure can then form the basis for more detailed studies by focussing attention on the critical nonpoint source areas, or combinations of factors leading to nonpoint source pollution (for example the combination of steep slopes and certain land use types). Similarly, the procedure can readily be modified to address other nonpoint source problems if an understanding of the problem exists.

However, while the model identifies potential production areas, it does not model the production and delivery mechanisms in detail. As such the model can not be used for simulating the likely effects of waste prevention and waste minimisation management practices. In addition, this method does not allow for a quantitative assessment of the nonpoint source contributions from different land uses. It is therefore only suited to a screening and scoping level of assessment, where the manager simply wants to focus on potential nonpoint source production areas. It consequently focuses management attention on the most important land use types, and on the most important areas. As such the method typically answers the management question "Where are the critical nonpoint source areas in the catchment".

Other similar models are discussed in sections 4C and 4E of the Guide (Pegram and Görgens, 1999).

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# 4 SIMPLE DETERMINISTIC AND STATISTICAL MODELS

### G Quibell and MP Matji

### 4.1 Introduction

The nonpoint source assessment technique presented in the previous chapter provides maps of potential nonpoint source areas on a qualitative basis. This focuses management attention on the most likely nonpoint source problem areas. However, managers may wish to more directly compare the nonpoint source loads from different catchments. In addition, when both point and nonpoint sources contribute to pollutant loads, it may be important to identify which of these contribute most significantly to observed water quality problems. This requires a more quantitative approach to nonpoint source assessment. More quantitative estimates of total nonpoint source loads may also be required as inputs for downstream models (for example where nonpoint source nutrient loads are required by reservoir eutrophication models).

This chapter describes the use of simple deterministic and statistical models to provide these more quantitative assessments of nonpoint source pollutant loads. This work is based on the work by Weddepohl and Meyer (1992), who describe the development and application of the deterministic "Phosphorus Export Model" (PEM), as well as various statistical means of determining phosphorus loads. Matji (2000) describes a range of successful parameter transfer test of the PEM model for different single land use dominated catchments in the Western and Eastern Cape Provinces.

# 4.2 The approach used in simple Statistical and Deterministic models

### 4.2.1 Background

Simple deterministic and statistical models are based on the assumption that most nonpoint sources are driven by hydro-meteorological events, and use the empirical relationship between stream flow and pollutant concentrations to calculate nonpoint source loads.

Statistical models comprise the relationship between stream flow and pollutant concentrations, and use this relationship, together with simulated or observed stream flow to simulate total pollutant loads. Simple deterministic models similarly use observed or simulated stream flow data as the basic input variable, but associate pollutant loads with conceptually simplified processes that lead to nonpoint source pollution. These tools are described in more detail below.

### 4.2.2 Statistical models

Statistical models are commonly used when modelling nutrient loads as part of reservoir eutrophication studies. Examples of this approach are the Jones and Lee (1982) OECD model, the FLUX model (Walker, 1987), the Reservoir Eutrophication Model (REM) (Grobler and Rossouw, 1988) and the Reservoir Specific Eutrophication Model (RSEM, Weddepohl and Meyer, 1992). These models are based on the premise that nonpoint source loading of nutrients (mainly phosphorus in these cases) is primarily a function of the production of stream flow. Phosphorus Load (P) is associated with stream flow (Q) in the following way.

P= aOb

<sup>&</sup>lt;sup>5</sup> This chapter does not provide a detailed description of the models, and is only intended to illustrate the management applications of this type of nonpoint source assessment tool.

Where, "a" and "b" are determined by regression of stream flow and phosphorus concentrations. Pollutant loads are calculated from observed or simulated stream flow data using this relationship.

The various methodologies described above have provided refinements of this basic concept to more accurately estimate total phosphorus loads. These models lump all the catchment characteristics and nonpoint source processes into a few statistically calibrated parameters. Statistical models are therefore useful where accurate stream flow and concentration data are available, but where there is little or no data available for catchment land use. However, these techniques provide estimates of total pollutant loads, and do not separate point and nonpoint source loads, or loads from different land uses.

Bath (1986) developed methods of separating loads for different parts of the hydrograph. The FLUX model similarly allows the user to "stratify" the flow data to provide for different regressions for high and low flows. These two techniques can therefore be used to separate base, and hence point source dominated loads, from storm, and hence nonpoint source dominated loads. Total loads from nonpoint source dominated catchments may also be compared to point source dominated catchments to assess their relative contributions. Similarly, catchments dominated by single land use types may be compared to infer the relative impacts of different land use types.

Statistical assessments of pollutant loads tend to be catchment specific, and the calibrated parameters are not transferable to other catchments. Similarly, the methodology does not take account of changing land use patterns or management practices and the impact these have on pollutant loads. This makes it difficult to assess the effects of future changes to the catchment, and limits their value as predictive tools.

# 4.2.3 Simple Deterministic models (PEM)

The Phosphorus Export Model is a simple deterministic model, which was developed to simulate the accumulation and washoff of phosphorus from nonpoint source dominated catchments. As a deterministic model PEM further unravels the processes causing the accumulation and washoff of phosphorus in catchments. However, PEM uses a lumped parameter approach, where the multitude of factors which contribute to phosphorus accumulation and washoff are grouped into a relatively small number of factors which are averaged across the catchment. These factors are calibrated into the model using observed phosphorus loads.

PEM estimates total phosphorus loads as the sum of soluble, particulate and groundwater loads (Fig 4.1). The model uses simulated or observed surface runoff (Q) together with a phosphorus wash-off parameter (SPAR), to simulate soluble phosphorus loads (SP). Sediment production (SED) and surface runoff are used to simulate particulate phosphorus loads (LP)<sup>6</sup>. Similarly, the groundwater component of stream flow, together with estimations of the phosphorus concentration of groundwater interflow, may be used to simulate groundwater contributions to total phosphorus loads<sup>7</sup>. Surface washoff of phosphorus is also affected by the surface accumulation of phosphorus (recharge) onto the catchment, which in turn influences the availability of phosphorus for wash off (Fig 4.1).

<sup>7</sup> This component is thought to be negligible in most catchments (Weddepohl and Meyer, 1992).

<sup>&</sup>lt;sup>6</sup> Most of the nonpoint source phosphorus load is thought to be carried on sediment (McElroy et al, 1976)

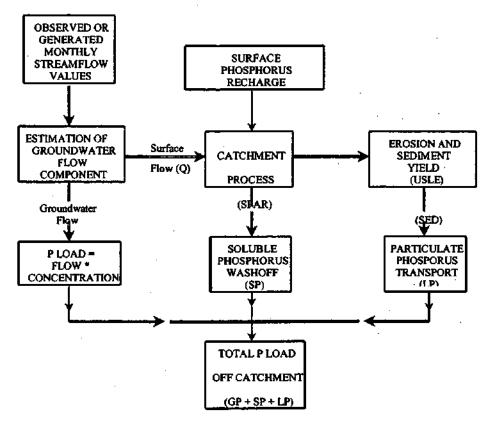


Figure 4.1 PEM's simulation of total phosphorus loads (from Weddepohl and Meyer 1992).

The most important component of the total nonpoint source phosphorus load is that associated with the sediment washed off of the catchment. Simulations of sediment production therefore form one of the most important components of the model. Sediment production is based on the Universal Soil Loss Equation (USLE), which uses rainfall intensity, slopes, soil erodibility, land cover and management factors to simulate sediment washoff (see previous chapter). As such PEM uses the USLE land use divisions to discretise the catchment into 10-100km² units. The model can simulate a maximum of 20 land use units per catchment. However, only in terms of their differing sediment loss potential.

PEM is a monthly time step model, which may be calibrated using the observed monthly stream loads in gauged catchments. However, being primarily based on sediment production, the model is most effective in catchments were the dominant nonpoint sources of phosphorus are agricultural. Similarly, the USLE was intended to model sediment delivery from small agricultural plots, this questions the accuracy of simulated phosphorus loads in larger catchments. Lastly, detailed knowledge of the catchment is necessary to estimate the initial phosphorus storage parameters, as well as those land management factors that influence sediment production.

### 4.3 Using these models in management

Simple quantitative nonpoint source assessment tools represent the next step in meeting managers' needs with respect to managing nonpoint sources of pollution. Their advantage is that they provide

quantitative nonpoint source loads in mass per unit area, at a range of temporal scales. (Unlike the GIS based model presented in the previous chapter). These tools can directly compare loads from different catchments or sub-catchments to focus management attention on those with the greatest contribution to observed problems. Similarly, loads from point source dominated catchments, may be compared to nonpoint source dominated catchments to identify their relative contributions to the overall problem. These tools also have the advantage that, as lumped parameter models, they are relatively easy to calibrate. The quantitative output of these models may also be used as input into other models.

However, statistical models lump all of the catchment processes into a single "black box" statistical function. The models also simulate total pollutant export (production + delivery + transport) from gauged catchments., and do not separate the land uses which contribute most to the nonpoint source problem. Similarly, the models do not separate point and nonpoint sources of the pollutant. This means that the relative contributions of different land uses, or of point and nonpoint sources, can only be inferred if the catchments are dominated by one land use type. In addition, simulations are dominated by the flow data used as input and the effects of changes in land use over the calibration period are often swamped by the changes in flow. Simulations using predicted flow data also assume that the relationship between flow and concentration remains constant. This will only happen if land use remains the same. This limits their use as "what if" tools, particularly if the manager needs to assess the effects of changes in land use. As such stochastic tools should only be used to extend nonpoint source loading data to ungauged periods, or to provide more continuous input data to other models. Alternatively, these models can provide useful information to focus management attention on problem land uses, or on point or nonpoint sources where the gauged catchments are dominated by one land use type.

Simple deterministic models address some of these problems by unpacking some of the processes resulting in nonpoint source pollution. In PEM this is done by relating nonpoint source phosphorus loads to sediment production processes. By providing further insight into the processes of nonpoint source pollution these models increase their value as predictive tools, and hence broaden their uses for water quality managers. However, these models still have the disadvantage of lumping certain catchment nonpoint source processes into single calibrated parameters. (e.g. PEM's particulate and soluble washoff parameters). The value of these tools for "what if" scenario analysis is therefore restricted to testing changes in processes that have not been lumped. (PEM for example can only assess the effects of land use changes if the changed sediment production can be simulated by the USLE. The USLE is intended to simulate sediment washoff from agricultural plots. PEM therefore can not simulate changes in fertiliser application technique, or the effects of other land use changes on total phosphorus loads). Similarly, the model can not estimate the nonpoint source contributions from different land uses in catchments.

However, Matji (2000) has shown that the two parameters of the PEM model appear to be quite robust when transferred between gauged and ungauged catchments.

### 4.4 Conclusions

The models described above provide quantitative assessments of nonpoint source contributions from different catchments. These loads can then be compared to allow managers to identify the *relative* contributions from different areas. As such they support an evaluation level of management needs, and typically answer the management question: "What are the contributions of different catchments to the total nonpoint source load" (see Table 2.1).

However, these models are limited in their value for nonpoint source management purposes, primarily as they lump land use types and catchment nonpoint source production, delivery and transport processes. While this makes them easier to calibrate, it also limits their value as tools to predict the impacts of various nonpoint source management practices aimed at any of these processes. They are consequently most suited to catchments where their lumped parameter problem is not an issue, (eg. catchments that are dominated by a single land use type), or where managers do not want to identify management practices. These models must also be calibrated, which means that stream flow data and concentration data must be available.

Other similar models are discussed in sections 4D and 4E of the Guide (Pegram and Görgens, 2000).

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# 5 MODELS WHICH DISAGGREGATE CATCHMENT PROCESSES (THE CATCHMENT WASHOFF MODEL USED IN THE AMATOLE SYSTEMS ANALYSIS)

# GC Pegram and G Quibell

### 5.1 Introduction

The models described in the previous chapter, while providing quantitative data, were limited in that they lumped production, delivery and transport processes, and various land uses. This restricts their value to catchments that are relatively homogenous or where managers do not want to assess the effects of management practices. However, models and methodologies are available which disaggregate land use types and nonpoint source processes. This chapter describes one such model, the Catchment Washoff Model (CWM), which was used to simulate the nonpoint source contributions from different land uses in the Amatole System. The chapter is summarised out of the original work (xxxx, 19xx)

# 5.2 The Catchment Washoff Model (CWM) as part of Systems Analyses

Strategic planning around the management of South Africa's water resources is largely based on systems analysis, using the Water Resources Planning Model (WRPM), and the Water Resources Yield Model (WRYM). The development of the CWM was consequently based on the integration of these models with appropriate nonpoint source assessment techniques. More specifically the CWM was designed to:

- use hydrological information (rainfall and flow series) which is readily available from the general system analysis models (including the WRPM and WRYM); and
- produce water quality times series (loads) which can be input to river transport water quality
  model, which in turn provides input load time series to the reservoir water quality simulation
  model (IMPAQ).

### 5.3 Constituents modelled

The CWM was designed to simulate nonpoint sources of the following constituents:

- Sediment at a sub-catchment and monthly resolution;
- Phosphorus at a sub-catchment and monthly resolution; and
- E.coli (indicating microbiological pathogens).

The model, therefore, disggregates both the nonpoint source problems, and the land uses responsible for these problems. The following sections briefly outline how this disggregation was achieved.

### 5.4 Hydrology

### 5.4.1 Dissaggregation between surface runoff and basefl ow

The dissaggregation of surface runoff and baseflow provides the means to separate point source loads (associated with baseflow) and nonpoint source loads (associated mostly with surface runoff). The CSM separates surface washoff and baseflow using observed salinity loads and streamflow. Baseflow

salinity tends to be much higher than surface runoff concentrations. As such salinity records together historical flow records, before abstractions have been removed and point source discharges are added, can therfore be used to separate baseflow and surface washoff.

This was then also used to produce surface runoff and baseflow time series to drive the nonpoint source simulation of non-conservative constituents, based on generated streamflow time series. This makes the non-conservative washoff module consistent with the nonpoint source salinity simulation (in the system models).

## 5.4.2 Dissaggregation of the surface runoff between land uses

The major disadvantage of the models described in the previous section is that they aggregate land use, and as such they can not identify the relative loads from different land uses (unless the catchments are homogenous). However, land use based nonpoint source washoff modelling can overcome this problem. As different land uses contribute differently to the total runoff and may have significantly different contamination potential, this dissaggregation requires an estimate of the surface runoff and contamination associated with different land uses.

Disaggregation of surface runoff between land uses in the CSM was based on the simulation of daily rainfall-surface runoff using the SCS curve number equation, adapted for continuous simulation (Haith, 1985). The growing season reflecting vegetation cover conditions in the Amatole region was assumed to occur from October to April, according to seasonal rainfall and temperature variations. Time series of monthly rainfall vs. surface runoff were calculated from the daily simulations for a range of curve numbers.

To accommodate different rainfall patterns, the study area was divided into five rainfall zones, based on five stations that had been used for the monthly hydrology simulation. The analysis was performed using ten years of daily rainfall (1987 to 1996) at these stations. Few of the study area's rainfall stations had daily records available for these years. These five stations were assumed to represent rainfall conditions in the five rainfall zones.

Simplified relationships were developed for the five rainfall zones, to estimate monthly surface runoff (mm) given monthly rainfall (mm), for the range of SCS curve numbers associated with land use and soils in the Amatole system (i.e. 50 to 90). The relationships were assumed to be in the following form, which is the basis of a many rainfall - runoff relationships:

## Monthly Surface Runoff = $\alpha$ (Rainfall - $\beta$ )

Factors were selected according to their perceived fit against the generated data for different curve numbers in different zones. The dimensionless slope factor ( $\alpha$ ) was the only parameter which was found to vary significantly between zones and curve numbers, while the "detention" factor ( $\beta$ ) in mm varied linearly with curve numbers being similar for different zones, and the power factor ( $\gamma$ ) was a constant 1.67 for all relationships. Table 5.1 presents the factors estimated by this analysis.

Table 5.1. Parameters for the monthly rainfall - surface runoff power relationships.

Curve Number	50	60	70	80	90
β (mm)	120	95	70	45	20
Zone 1	0.005	0.0015	0.0035	0.0055	0.009
Zone 2	0.0025	0.0045	0.0065	0.0085	0.012

Slope: α	Zone 3	0.003	0.005	0.007	0.009	0.012
	Zone 4	0.002	0.004	0,006	0.008	0.0115
	Zone 5	0.004	0.006	0.008	0.01	0.012

These relationships are used to derive the rainfall - runoff curves for all the land uses in a given subcatchment, according to the curve numbers for the dominant soil group. The different land use categories which were deemed important from a nonpoint source perspective were grassland and bushveld (generally with livestock), indigenous forest, commercial timber, commercial crops (dryland and irrigated), rural settlements, informal settlements, and urban areas. Another land use category (riparian) was also included to account for the surface runoff that is generated from the saturated riverine and wetland riparian zones during small rainfall. This area was assumed to represent about 2.5% of each catchment and for the purposes of this simulation, was assumed to have the same runoff characteristics as grassland (i.e.  $\alpha$ ), except that runoff is generated earlier (i.e.  $\beta = 20$ ). Table 5.2. Areas (km²) associated with different land use categories by sub-catchment in the Amatole system (obtained through GIS analysis)

Sub-Catel	bmeat <sup>1</sup>	(mm)	MAR (mm)									krea (km	7)	<u> </u>			
	•		` '	ľ	Form	Gпр	Total	Riparien	Grass	Bush	Forest	Timber	Dryland	Irrigat.	Rural	Informal	Urban
Buffalo	1			· ·						_					·	·	
2001	Maden	1407	280	3	Mispah	C	30.0	0.3			25.7	4.0	Į I				
2020	Rooikrantz	1106	150	3	Mispah	С	18.8	0.5		3.5	13.9		0.9			1	
2008	Quencwe .	923	110	3	Mis/Glen	B/C	62.0	1.6		7.3	38.0	6.9	7.2		1.1		
2007	Zele	747	80	3	Glen/Mis	B/C	81.8	2.0		44.8	10.8	2.3	15.7	0.0	6.2		
2012	Jefta	1153	260	3	Glenrosa	В	15.1	0.4		4.0	9.2		1.3		0.2		
2006	Mgqakwebe	733	70	3	Glen/Mis	B/C	105.3	2.6		61.2	12.4	1.0	23.1		5.0	]	
2005	Buffalo (KWT)	652	70	4	Glen/Mis	B/C	100.6	2.5		63,9	1.9	-	19.8	1.3	8.2	2.4	0,6
2009	Mgkokweni	568	40	4	Mispalı	С	102.7	2.6	66.0		1		26.l	0.0	8.0		
2010	Buffalo (d/s KWT)	579	70	4	Mispah	С	158,7	4.0	92.5		ļ.		37.4	2.3	9.7	1.1	11.8
2011	Yellowwoods	662	70	2	Glen/Mis	B/C	196.3	4.9	124.8	•	9.1	0.3	41.1	0.6	5.0	8.2	2.4
2017	Laing	639	90	5	Mispah	С	48.5	1.2	32.1				11.1	0.1	0.4	1.5	2.1
2018	Bridle Drift	677	70	5	Hut/Mis	A/B	262.8	6.6	139.0		50.1		22.6	0.1	7.1	3.5	33.8
Ggunube																	
3001	Outspan	688	30	2	Glen/Hut	A/B	504.5	12.6	447.5	1	Į .	}	39.2	5.2	•	0.1	
Nahoon																	
3003	Natioon	672	60	2	Mis/But	В	476.7	11.9	407.3	1		<u> </u>	39.6	3.3	0.4	10.6	3.6
Kubusi	, .			$\vdash$		† <u> </u>	<u> </u>	1					<b>1</b>			1	· · · ·
6004	Gubu	882	150	1	Mispah	C	23.0	0,6	8.4	ļ	4.4	9.7				1	
6001	Stutterheim	887	200	1	Mispah	C	68.2	1.7	34.6	•	22.8	4.8	2.9	1.5		1	
6005	Wriggleswade	742	70	- T	Glen/Mis	B/C	363.3	9,1	227.5	}	27.0	55.4	35.3	4.3	0.5	1	4.4
Toise	<u> </u>	<u> </u>				†		1								1	
6003	Forkroad	672	90	4	Glenrosa	В	217.1	5.4	158.3	1	7.23	25.65	18.28	2.13			

Key: 1 The sub-catchment numbers are those used in the system model, which also provided the estimates of rainfall and runoff.

#### Hydrology Parameters for the Washoff Model 5.4.3

Table 5.2 presents the area under each of the land use categories, with an indication of the dominant soil forms, within each of the sub-catchments. Table 5.2 also indicates the rainfall zones, mean annual precipitation (MAP), Pitman estimated mean annual runoff (MAR), and hydrological soil groups for each sub-catchment. The Amatole system is dominated by Hutton, Glenrosa and Mispah soils (ENPAT data base), which are generally associated with SCS hydrological groups C, B/C and A, respectively. Table 5.3 presents the South African curve numbers associated with each of these land use categories and soil groups, based on values presented by Schulze (1995) and the Soil Conservation Service (Mills et al, 1985).

Table Soil Group	5.3. Curve	Number	s associat			and use can bers (Cl		and hydr	ological so	oil group
, 	Riparian	Grass	Bush	Forest	Timber	Dryland	Irrigat.	Rural	Informal	Urban
A	49	49	45	36	42	63	35	54	72	61
A/B B	61	61 69	56 66	49   60	54 65	69 74	41 48	63 70	77 82	69 75

75

82

68

73

The information presented in Tables 5.1, 5.2 and 5.3 may be used to develop sub-catchment specific \alpha and β parameters for different land use categories. These land use rainfall - runoff relationships (fi[Rain]), taken together with the area associated with each land use (A,) in a sub-catchment, are used to derive the proportion of the total surface runoff volume in month (m) generated from each land use in a sub-catchment, given the total rainfall. These proportions are then used to disaggregate the total surface runoff bet ween different land uses (i).

57

65

76

80

85

87

80

83

Surface Runoff<sub>im</sub> = 
$$\underline{Total\ Surface\ Runoff_m\ .\ f_i[Rain_m]\ .\ A_i}$$

$${}_i \{f_i[Rain_m]\ .\ A_i\}$$

The hydrological and salinity modelling estimates the direct surface runoff from impervious areas in peri-urban (informal) and urban areas separate from the pervious portion. Formal urban and informal peri-urban areas were assumed to be 20% and 10% impervious surfaces, respectively. The total input impervious surface runoff was distributed in this proportion between these land uses and added to the above-calculated pervious surface runoff.

The runoff simulation was based on existing hydrological timeseries and produced disaggregation results that were to be expected, and a detailed verification is not presented here.

#### Sediment 5.5

B/C

75

79

79

The main causes of sediment erosion and washoff are incorporated in the USLE approach (see Chapter 3), and this was therefore used as the most appropriate basis for nonpoint source sediment yield estimation in this model. The approach proposed by Mills et al (1985), based on work by Haith (1985), was adopted to disaggregate the long term sediment yield to provide annual and monthly estimates of sediment yield. This approach is based on an extension of the USLE in three different ways. Firstly, the rainfall erosivity factor (R) is related to monthly rainfall. Secondly, the portion of the long-term average sediment yield which is delivered from a sub-catchment (delivery ratio) is

related to the drainage characteristics (drainage density) of the sub-catchment. Thirdly, the annual sediment yield from each land use within a sub-catchment is actually delivered to the streams and rivers according to the relative surface runoff carrying capacity in each month of the "sediment year".

The following relationships between daily rainfall (mm) and erosivity (N.h<sup>-1</sup>.a<sup>-1</sup>) was used disaggregate the monthly rainfall erosivity to daily erosivity:

Daily Rainfall Erosivity = a (Daily Rainfall)<sup>1,81</sup>

A single calibrated annual scale factor (a) of 1.3 was used in this region, to reflect the spatial distribution (ranging from 180 to 300 N.h<sup>-1</sup>.a<sup>-1</sup>) of annual erosivity in the Amatole system. When the above daily relationship was used to determine the monthly erosivity rainfall relationship, the best fit against monthly rainfall (Rain, in mm was provided by the following equations:

The basic USLE parameters allow estimation of the production of sediment. A further parameter, the delivery ratio (DR) is used to estimate the actual sediment yield from a sub-catchment. DR may be related to catchment drainage density (McElroy et al, 1976). Drainage density may be estimated for each sub-catchment, based on the total length of rivers in the sub-catchment divided by the total area. In the Amatole system, average drainage density ranges from about 1.0 km/km² in the middle catchment to about 5 km/km² on the escarpment upstream of Maden Dam. This corresponds to a range in delivery ratios of about 0.35 to 0.5. Table 5.5 presents the assumed average drainage densities and associated delivery ratios (DR) for each sub-catchment. Delivery ratios may be modified according to the sub-catchment areas, with larger catchments having relatively lower sediment yield (Mills et al, 1985). This was not done in this study, because the estimated delivery ratios were consistent with the calculated ratios between the estimated USLE values and reservoir sedimentation rates estimated by Rooseboom et al (1992) for Maden, Gubu, Laing and Bridle Drift Dams,

The USLE requires values for soil erodibility (K), slope length (LS) and land cover and management practices (CP). The resolution of the available soils and topographic data only allowed the derivation of average K (ton.h.N<sup>-1</sup>.ha<sup>-1</sup>) and LS (dimensionless) values for each sub-catchment, while the CP (dimensionless) factor is land use specific. Although, parameter lumping reduces the possible accuracy of the approach, the catchments are relatively homogeneous and generally small enough to provide adequate estimates for this study. It also enables future land use development scenarios to be tested without having to specify exactly where in the sub-catchment it would occur.

Hutton, Glenrosa and Mispah soils are dominated by moderate, moderate-high and high-moderate erodibility classes, respectively, corresponding to soil erodibility (K) factors of 0.4, 0.45 and 0.5. These factors were averaged over each sub-catchment in the approximate proportion of total area (see Table 5.5). The LS factors for each sub-catchment were derived from average sub-catchment topographic gradient (%). The assumed slopes and resulting LS factors are presented in Table 5.5.

Table 5.5. Sediment parameters associated with each subcatchment in the Amatole system.

Sub-Catchment	Area (km²)	Drain	lage	Soi	l ·	Slope		CX <sub>base</sub> (mg/l)	
		km/km²	DR	Form	K	%	LS	, ,	
Buffalo		<del>                                     </del>							

2001	Maden	30.0	3	0.45	Mispah	0.50	- 8	3.1	10
2020	Rooikrantz	18.8	3	0.45	Mispah	0.50	5	1.9	10
2008	Quencwe	62.0	2	0.4	Mis/Glen	0.48	5	1.9	10
2007	Zele	81.8	2	0.4	Glen/Mis	0.47	5	1.9	10
2012	Jefta	15.1	3	0.45	Glenrosa	0.45	8	3.1	10
2006	Mgqakwebe	105.3	2	0.4	Glen/Mis	0.47	5	1.9	10
2005	Buffalo (KWT)	100.6	1	0.35	Glen/Mis	0.47	2	0.65	10
2009	Mgkokweni	102.7	1	0.35	Mispah	0.50	2	0.65	10
2010	Buffalo (d/s KWT)	158.7	1	0.35	Mispah	0.50	2	0.65	10
2011	Yellowwoods	196.3	1	0.35	Glen/Mis	0.47	3	1.05	10
2017	Laing	48.5	1	0.35	Mispah	0.50	3	1.05	10
2018	Bridal Drift	262.8	2	0.4	Hut/Mis	0.45	5	1.9	10
Gqunube									
3001	Outspan	504.5	1	0.35	Glen/Hut	0.42	3	1.05	10
Nahoon									
3003	Nahoon	476.7	1	0.35	Mis/Hut	0.45	3	1.05	10
Kubusi	,			[					
6004	Gubu	23.0	3	0.45	Mispah	0.50	8	3.1	10
6001	Stutterheim	68.2	2 -	0.4	Mispah	0.50	5	1.9	10
6005	Wriggleswade	363.3	1	0.35	Glen/Mis	0.47	2	0.65	10
Toise									
6003	Forkroad	217.1	2	0.4	Glenrosa	0.45	3	1.05	10

Table 5.6 presents the land use related CP factors, based on a synthesis of information presented in Schulze (1995) and Mills et al (1985). The annual sediment yield (ton/km²) from land use (i) with area (A<sub>i</sub> in km²) in each sub-catchment is given by:

Sediment can only be delivered into streams by surface runoff. The proportion of the available sediment delivered in any one month is related to the carrying capacity of the surface runoff during that month. Mills et al (1985) propose that a 1.2 power function of the monthly surface runoff be used. However, these only provide estimates of the relative carrying capacity of monthly surface runoff within the year, in order to distribute the annual sediment yield over time. The sediment yield from land use (i) in month (m) is calculated by distributing the annual sediment yield from that land use, as follows:

Sediment Yield<sub>im</sub> = Annual Sediment Yield<sub>i</sub>. (Total Surface Runoff<sub>m</sub>)<sup>1,2</sup>

$$3_{m=1,12} \{ (Total Surface Runoffm)^{1,2} \}$$

Table 5.6 Sediment, phosphorus and E.coli parameters associated with different land use categories.

Parameter		Land use								
	Riparian	Grass	Bush	Forest	Timber	Dryland	Irrigat.	Rural	Informal	Urban
Sediment CP:	0.028	0.028	0.025	0.001	0.002	0.15	0.01	0.1	0.2	0.15
Phosphorus $ \varsigma_i \text{ (mg/l)} $ $ \exists_i \text{ (mg/l)} $ $ (_i \text{ (mg/g)} $	0.01 0.01 0.22	0.01 0.01 0.22	0.01 0.01 0.22	0.005 0.01 0.22	0.005 0.01 0.22	0.01 0.1 0.22	0.01 0.1 0.22	0.05 0.1 0.22	0.2 0.8 0.22	0.3 0.6 0.22

E.coli										
( <sub>i</sub> (#/100ml)	10	10	10	0	0	0	10	100	1000	500
$_{0}(10^{10}/\text{ton})$	0.1	1.0	0.1	0	0	0	0.1	10	100	100

This approach assumes delivery of all the available sediment within each year, which implies that the sediment year should end with significant flushing events. In the Eastern Cape, this implies that the sediment calculations should be from April to March, to end with the large storm events of late summer.

The baseflow carries a relatively small sediment load, but it should be estimated to take account of low flow adsorbed nutrient dynamics. This was estimated using a constant average baseflow sediment concentration (CX<sub>base</sub>) for each sub-catchment (see Table 5.5) multiplied by the estimate of the baseflow volume (10<sup>6</sup> m<sup>3</sup>) in each month. This is added to the sum of the sediment yield from each land use in that month to provide the total monthly sediment export load (ton/month) from the sub-catchment.

Sediment Export Load<sub>m</sub> = 
$$CX_{tase}$$
. Baseflow<sub>m</sub> +  $3_i$  { Sediment Yield<sub>im</sub> }

Table 5.7 overleaf presents the simulated sediment loads in each sub-catchment, together with the esitmated contribution as a percentage of each of the landuse types simulated. This then allows the manager to not only identify which sub-catchments contribute most to the observed problems, but also to assess the relative contributions of the various landuse types. Dissaggregation of land use therefore provides significantly more information to the managers, than that provided for by simple statistical and deterministic models. However, this is at the expense of model complexicity.

Sub- Catchment	Annual Load (ton/a)	C	ontributio	n to Sedime	ent Load (*	<b>(6)</b>	Load (	ton/km²)
	<u> </u>	Riparian	Veld	Wood	Crop	Settle.	Est.	Roose.
Buffalo		-				<u> </u>		
2001	1400	20	0	80	0	0	44	42
2020	2000	8	50	11	31	0	140	
2008	8500	8 5	17	6	64	8	230	
2007	19 000	2	37	1	46	14	375	
2012	5600	4	33	3	55	5	130	İ
2006	17 000	2	41	0	49	8	70	
2005	9200	1 1	26	0	48	25	80	
2009	8300	1	32	0	55	12	90	
2010	14700	1 1	22	0	45	32	130	] .
2011	30 000	1 1	32	0	42	25	150	1
2017	8300	1	29	0	44	26	170	(75)
2018	58 000	1	27	0	15 _	57	221	750
Nahoon							1	
3003	54 000	2	58	0	. 24	17	114	115
Kubusi	•					<del> </del> -		
6004	3000	6	85	9	0	0	128	161
6001	9400	0	70	2	28	1	140	
6005	17000	2	50	11	41 _	6	50	<u> </u>
Toise 6003	14900	2	60	ı	37	0	70	

#### **Fable 5.7.** Simulated sediment loads. The following values are based on average estimates

## 5.6 Phosphorus

Total and soluble phosphorus nonpoint source washoff was also simulated in the CSM. The well established loading function approach (Haith and Schoemaker, 1987; McElroy et al, 1976; Mills et al, 1985) was used to determine monthly nonpoint source phosphorus loads (yield) from each land use in each sub-catchment. This was done for each land use category in the case of surface washoff. It was assumed that the contribution of each land use to baseflow was proportional to the area of that land use relative to the total area (TA) of the sub-catchment. This accounts for direct use of rivers for washing, bathing and animals, as well as sewage and grey water discharge through infrastructure failure, in areas of human habitation. The particulate and soluble phosphorus loads (kg/a) are made up of a baseflow and surface washoff component in a sub-catchment. These may be calculated using the following equations:

Particulate Phosphorus<sub>m</sub> = (en) 
$$3_{i} \{ (A_{i}, (CX_{two}, Baseflow)) + ((.Sediment Yield_{im})) \}$$

$$TA$$
Soluble Phosphorus<sub>m</sub> =  $10^{3}.3_{i} \{ (A_{i} \forall_{i}.Baseflow_{m}) + (\exists_{i}.Surface Runoff_{im}) \}$ 

 $\forall_i$ ,  $\exists_i$ , and ( i are the loading coefficients reflecting average concentrations of phosphorus in baseflow, surface runoff and sediment from land use i, and are presented in Table 5.6. These were derived and synthesised from information presented in Haith and Schoemaker (1987), McElroy et al (1976) and Mills et al (1985), together with South African data summarised in Pegram et al (1997). The enrichment of particulate phosphorus concentrations, due to the washoff of a higher portion of finer materials with relatively higher adsorption potential, is represented by the enrichment ratio (en), which has been observed to have an average value of about 2.0 (Haith and Shoemaker, 1987).

As with sediment, disggregation also allows the manager to assess the relative contributions to nonpoint source phosphorus loads from differ sub-catchments, and from different landuses (Table 5.8).

Table 5.8. Simulated average annual soluble (SP) and total (TP) phosphorus loading in the Amatole

system.

Sub- Catchment		Phosphorus l (kg/a)	Land	use contr Phosp	oluble	Areal Load (kg/km²)			
	SP	TP	Ripar	Veld	Wood	Crop	Settle	ŞP	TP
Buffalo		'							
2001	70	800	6	0	94	0	0	2.2	25
2020	30	1100	3	13	41	44	0	1.5	60
2008	130	4700	2	4	22	63	8	2.1	75
2007	200	11 000	2	11	2	64	21	2.5	130
2012	80	3200	6	10	13	65	6	5.4	210
2006	190	9 500	3 2 2 6 2	12	2	72	12	1.8	90
2005	440	4100	1	6	0	28	65	4.6	40
2009	120	3800	2 0	13	0	68	18	1.2	40
2010	1400	6 000	Ó	3	0	13	84	8.8	40
2011	1100	14 000	0	4	0	18	78	5.5	70
2017	380	3900	0	4 .	0	18	78	7.8	- 80
2018	2700	27 000	0	2	0	_4	94	10	100
Nahoon									
3003	1700	25 000	1	8	0	12	80	3.6	50
Kubusi				<u> </u>					
6004	29	1000	12	42	46	0	0	1.3	45
6001	170	4300	6	35	16	43	0	2.5	65
6005	850	8 000	3	11	2	26	58	2.4	20
Toise									
6003	310	7 000	7	27	3	63	0	1.4	30

## 5.7 Microbiological Contamination

A loading function approach, as proposed by Gilliland and Baxter-Potter (1987), was adopted to simulate faecal contamination. This approach was, however, modified for inclusion into the CWM. *E.coli* load may be assumed to occur during both baseflow periods and surface runoff events. Microbiological pathogens (and their indicators) are mobilised and transported by similar processes as sediment, and are often adsorbed onto sediment. As the availability of faecal bacteria is also highly related to land use, storm washoff of *E.coli* was simulated as a potency factor (0<sub>i</sub> in 10<sup>10</sup> MPN/ton) on the sediment yield from each land use. A land use related baseflow concentration (8<sub>i</sub> in MPN/100ml) was assumed to reflect direct contamination and infrastructure failure. Thus the total monthly *E.coli* load (10<sup>10</sup> MPN) may be calculated by:

$$E.coli_m = Baseflow_m.3 {A_i.8_i} + {0_i.Sediment Yield_{im}}$$
TA

The parameters 0<sub>i</sub> and 8<sub>i</sub> are presented in Table 5.6 for each land use, based on expected soil and baseflow concentrations associated with each land use. These values were derived from literature values (Pegram et al, 1998; Baxter-Potter and Gilliland, 1988) modified according to estimated *E.coli* application rates (Pegram et al, 1996). The highly variable nature of *E.coli* concentrations implies that order of magnitude values are adequate (or at least the most reasonable, given our limited knowledge). Open veld and irrigated areas are assumed to have small *E.coli* loading, because these

areas are generally used to graze cattle in the Amatole system. However, the predominant microbiological loading comes from densely settled areas (Table 5.9).

Loads only provide an indication of the source of microbiological contamination, whereas the acute and localised nature of the problem requires an estimate of *E.coli* concentrations, during runoff events and baseflow periods. The average *E.coli* concentration (#/100ml) in surface runoff from each land use category, as well as the average concentration in baseflow during a month, may be estimated by:

Surface E.coli Concentration<sub>im</sub> = Sediment Yield<sub>im</sub>
Surface Runoff<sub>im</sub>

Baseflow E.coli Concentration<sub>m</sub> = 
$$3_i \{\underline{A_i} \cdot \forall_i\}$$
TA

These concentrations are only order of magnitude estimates, and are only relevant for the smaller sub-catchments, because die-off has a significant impact on these concentrations as they are transported downstream in the receiving water environment. Nevertheless the methodology also allows an assessment of the relative contributions from different sources. (A more detailed analysis of faecal contamination is outlined in the following chapter.)

Table 5.9. Average long term average baseflow and surface runoff E.coli concentrations.

	E.coli Concent	rations (#/100ml)	Land use co	ntribution	(%) to <i>E.col</i>	i load in su	rface runof
	Baseflow	Surface Runoff	Riparian	Veld	Wood	Crop	Settle.
Buffalo							
2001	0	7 .	100				•
2020	2 3	50	15	85			
2008	3	2300	1 1	85 2 2 7 5	٠ .		97
2007	15 5	8200		2	1		98
2012	5	3900	٠,	7			93
2006	10	5000		5			95
2005	40	15 000					100
2009	15	4100		2	[ ·		98
2010	50	26 000			į l		100
2011	60	80 000	l l				100
2017	60	76 000					- 100
2018	90	300 000				.,	100
Nahoon				,			
3003	35	50 000					100
Kubusi							
6004	5	140	10	90			
6001	6	. 92	5	95	1		
6005	_15	3900	_ [	2	1	-	98
Toise							
6003	10	100	3	97	}		

## 5.8 Conclusions

The Catchment Washoff Model provides several advantages over the simple statistical and deterministic models presented in the previous chapter. Firstly, the model simulates a greater level of detail with respect to the processes that result in nonpoint source pollution. The model is consequently a closer representation of catchment nonpoint source processes (i.e. production + delivery or yield), and as such requires less calibration. More importantly, the model uses fewer lumped parameters, and allows the user to separately assess the nonpoint source loads of a range of variables from a number of different land use types. This means that the manager can not only more accurately assess the relative

contributions of nonpoint and point sources, but can also rank nonpoint source contributions from different land use types in each sub-catchment. This information can then be used to focus management attention on priority sources, especially where several land use types may contribute to the observed problems.

The inclusion of different land uses, and the monthly temporal scale also allow the user to assess the likely effects of future changes in land use, which can then be linked to the effects of increased water demands, or the development of new water supply schemes. This model consequently supports a prioritisation level of management needs.

The model does not, however, model the detailed nonpoint source production and delivery processes on each land use type, and rather uses a potency factor approach to assess the production potential. Similarly, the delivery of the pollutants is assessed by the delivery ratio approach. This limits the use of the model to assess the effects of nonpoint source management practices aimed at limiting the production and delivery of pollutants. As such the model can not support the selection of management practices.

In addition, the greater level of detail in the model is at the expense of simplicity and ease of use. The CWM is more complex than those outlined in the previous chapter, and requires a greater understanding of nonpoint source pollution problems. Its use should, therefore, be restricted to situations where a number of nonpoint sources contribute to observed problems, and there is uncertainly as to which of these are the most significant, or to cases where managers need to assess the effects of different water resources planning options on water quality.

Other similar models are discussed in sections 4F and 4G of the Guide (Pegram and Görgens, 2000).

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# 6 DETAILED MODELLING OF NONPOINT SOURCE PROCESSES (AN URBAN FAECAL CONTAMINATION MODEL)

## G C Pegram and G Quibell

#### 6.1 Introduction

The model presented in the previous chapter allowed for the calculation of nonpoint source loads from various land uses by disaggregating the washoff and pollutant production potential of each land use type. However, the model still lumped the nonpoint source production and delivery processes into yield. As such the model can not be used to assess the effects of management practices specifically aimed at production and delivery processes. The selection of management practices aimed at these processes requires models that provide for detailed modelling of the production and delivery mechanisms. These are usually focussed on one particular land use type, and one water quality variable. This chapter describes the development of one such model, which assesses the impacts of faecal contamination from poorly serviced settlements. This work was done on the Camps Drift catchment, which forms part of the Mgeni River catchment, and forms part of a larger study aimed at identifying management options for nonpoint sources of pollution in the catchment.

## 6.2 Background

This chapter describes the investigation of *E.coli*, as an indicator of faecal contamination, in a 150 km<sup>2</sup> peri-urban catchment of the Msunduzi River upstream of Pietermaritzburg. The objective of the assessment was to rank the sources and processes contributing to faecal bacterial contamination flowing into a downstream urban recreational and flood control impoundment called Camps Drift, as well as to evaluate the impact of possible management strategies. Thus, the assessment supports the prioritisation of the sources in terms of their impact and manageability, as well as the selection of management practices.

Most of the water quality problems in the Mgeni River catchment are nonpoint source dominated. This required the development of an approach, which provided a management perspective on the physical processes governing nonpoint source contamination and its impacts within a catchment (Pegram et al., 1995). The approach was based on the definition of production at source, delivery to the receiving water bodies, transport in those water bodies and finally water use (see chapter 2).

The processes governing *E.coli* delivery, transport and die-off required that the analysis was performed seasonally, to reflect temperature and flow differences, and for high and low flows during summer, to represent the delivery associated with surface runoff during summer storms. The following discussion does not present the detailed model relationships and parameters. Rather it indicates the philosophy and assumptions behind the modelling approach, which were deemed necessary to reflect the processes governing faecal contamination from these types of settlements.

## 6.3 The production (source) areas

The main production areas for faecal contamination upstream of Camps Drift are associated with human settlement. The most important settlement characteristics that were assumed to determine the contribution to faecal contamination include:

- total population (and livestock): related to per capita production.
- housing type: formal, mixed formal/informal, informal (shacks) and transitional (rural-urban), which affects production and delivery.
- water supply infrastructure: on-site (in-house and yard-taps), communal (standpipes and boreholes) or other (springs, streams and water tankers), which affects production and delivery.
- sanitation infrastructure: sewer or on-site (pit-latrines, bucket-system, septic tanks and nothing), which affects delivery.
- hydrometeorlogical characteristics: rainfall, surface runoff and sediment production, indicating the potential delivery mechanisms.

The main sources of faecal contamination were identified using these characteristics and the detailed information presented in Table 6.1. The Henley release represents the inflow to the Pietermaritzburg sub-catchment from Henley Dam. The settlements in the upper catchment, including KwaMbanjwa, Sweetwaters, Smeru and Sinathingi, have a combination of medium density transitional, informal and formal settlements with low levels of water supply and sanitation (WSS) infrastructure. This is also a very steep area with a high runoff. The settlements in the central and lower catchment range from largely informal settlements with low levels of WSS infrastructure, such as KwaMpumuza, KwaPata, Phayiphini and Slangspruit, through mixed formal-informal settlements, including Sigodini, Edendale and Wilgefontein, to predominantly formal areas with full WSS service provision, such as Mbali and Ashdown. Sewer mains represent the contribution from leaking or overflowing trunk sewers located along the Msunduzi River, which service the upstream settlements.

Table 6.1. Description of the faecal contamination sources in the Camps Drift catchment.

	Source	Population (people)	Housing Type	Wa	ater Supply (	%)	Sanitat	ion (%)
#	Name .			on-site	communal	other	sewered	on-site
0	Henley release	-	-		-	-	-	-
la	KwaMbanjwa	4000	Informal		50	50		100
16	Sweetwaters	15 000	Informal		50	50		100
1c	Smeru	4000	Transitional		50	_50		100
2	Sinathingi	16 000	Transitional		70	30		100
3	Sigodini	4000	Mixed	40	60			100
4	KwaMpumuza	9000	Informal		70	30		100
5	Edendale	12 000	Mixed	40	60			100
6	KwaPata	7000	Informal	30	40	30		100
7a	Mbali	14 000	Formal	90	10	_	90	10
7b	Mbali	27 000	Formal	90	10		90	10
- 8	Phayiphini	4000	Informal		60	_40		100
9_	Ashdown	8000	Formal	100			100	
10	Wilgefontein	9000	Mixed	40	40	20	40	60
11	Slangspruit	5000	Informal		70	_30		100
12	Sewer mains	(50 000) <sup>1</sup>	-	-	_	-	-	-

These settlements include most of the inhabitants of the Camps Drift catchment. Any people that have not been counted, live in very sparsely settled areas on the fringes of the catchment, so have little impact on the faecal contamination in Camps Drift.

#### 6.4 Production and Delivery of Faecal Contamination from these areas

Production and delivery of faecal contaminants is largely associated with the source type (as outlined above) and season. The Camps Drift catchment has a wet summer and dry winter climate. The assessment was therefore performed for three flow and temperature regimes, namely winter (cold baseflow), summer low flows (warm baseflow) and summer high flows (storm flow), which were assumed to occur 50%, 40% and 10% of the time, respectively. This section elaborates the assumptions behind the derivation of *E.coli* production and delivery factors.

Faecal contamination is produced by humans or animals (livestock and pets), so the human and animal population determines the daily production of *E.coli* at the source. The availability of the *E.coli* depends upon the housing, sanitation and water supply infrastructure, as this determines where and how waste is removed, deposited on-site or accumulates on the land surface. Three production mechanisms were assumed.

- human waste associated with sanitation, either deposited on-site or removed by sewers.
- washing and sullage associated with water supply, either on-site, communal or limited supplies.
- accumulation on the land-surface associated with housing type, infrastructure and services, due to animal, human and household waste disposal.

*E.coli* dies off with time, so does not accumulate indefinitely. Eventually production occurs at the same rate as die-off, at which time a "steady state" is reached. Thus, the potential for *E.coli* delivery from the source to a receiving water body (stream, river or Camps Drift) depends on the production, die-off and removal rates. The on-site (soil or pit latrine) die-off coefficient (k) for *E.coli* was taken as 0.3 day<sup>-1</sup>, where the concentration is represented by:

$$C_t = C_0 \cdot e^{-kt}$$
.

This implies a steady state potential of four times the daily production. Three processes were assumed to govern delivery potential.

- production is removed every day (eg. by sewers), with potential equivalent to daily production.
- waste accumulates and dies off in on-site sanitation, until a steady state is reached.
- waste accumulates and dies off on the land surface, until steady state is reached.

The housing, water supply and sanitation infrastructure also influence delivery to receiving water bodies. This determines the fraction of the potential that is actually delivered. Four mechanisms were assumed:

- direct deposition to the water bodies by human and animal activity in or on the stream banks.
- surface washoff during storm events, including storm related failure of sewers and on-site sanitation.
- seepage of sullage, on-site sanitation or sewage from leaking collector sewers at the source.
- overflow or leaking of main trunk sewers between the source and the regional waste water works.

Loading factors were estimated in total loads per capita for the settlements and flow regimes. These factors were applied to the characterisation of the sources (settlements) in terms of population, water supply, sanitation infrastructure and housing type, to estimate the average (median) production, potential and delivery from each source during each flow regime.

The washoff from the land surface is dependent upon the carrying capacity of storm runoff in a particular area, so delivery during summer high flows is source dependent. The factor chosen to represent the delivery factor in runoff was based on the ratio of quickflow (surface runoff and

interflow) to total rainfall, as estimated using the ACRU hydrological simulation model (Kienzle et al., 1997).

## 6.5 Transport and Assimilation in the Receiving Water Bodies

Once *E.coli* have been delivered to a stream or river, they are transported by advection in the streamflow to Camps Drift. Die-off of *E.coli* may occur during this transport process, and is largely dependant upon the time of travel, the water temperature and the solar radiation (season and turbidity of the water).

Time of travel depends upon the flow velocity and distance travelled. Flow velocities were calculated using Manning's equation, based on slopes, manning's n and channel cross-sections. Channel form differs throughout the catchment, so four channel types were identified, namely:

- small tributaries, including the Mabane, Mvubikazi, KwaPata and other little streams,
- large tributaries, including the Sinathingi, Slangspruit and Wilgefontein Rivers,
- the steep upper Msunduze River above the Sinathingi confluence, and
- the lower Msunduse flowing through the Edendale valley.

Estimates of average flow conditions in each of the three periods (winter, summer low, and summer high) were based on ACRU simulated flows, which represented the general flow conditions in those channel types. This allowed the estimation of average flow velocities, which ranged from about 0.3 m/s in the small tributaries during winter to over 2 m/s in the upper Msunduze during summer high flows. These were used, together with the distance traveled, to estimate time of travel. The seasonal die-off rates for E. coli in the rivers were assumed to be 0.03 hour for the mean water temperature of 13°C during winter and 0.06 hour for the 21°C mean summer temperatures, based on preliminary site specific investigations and literature values (Crane and Moore, 1986). This was then used to estimate die off in the rivers upstream of Camps drift.

## 6.6 Ranking the Source Contributions

The delivery of *E.coli* to the rivers (as a load) and the fraction lost in transport were used to estimate the loading into Camps Drift. The average flow rates during different periods throughout the catchment were derived from the ACRU simulations, allowing concentrations to be estimated. Table 6.2 compares these to the observed long-term median concentrations at four Umgeni Water sampling sites. The observed concentrations at the Henley outflow were used to estimate the inflow load for the model and some calibration of general source type loading rates was performed.

The results outlined in Table 6.2 are acceptable, although the summer high flow concentrations from the Slangspruit seem to be too high. This may be attributed to under estimation of the streamflow by ACRU, or by too high an estimate of the impact of leaking collector sewers in this area. Alternatively, the samples may have missed most of the leaking sewer events.

**Table 6.2.** Comparison of estimated and median observed *E coli* concentrations (in counts/100ml) for the three flow regimes.

- VOUILD 1	001H1) 101 644	* ************************************	TOBILITON,			
Site	winter		summer low flows		summer high flows	
	Est	o <b>b</b> s .	est	obs	bypass	obs
Henley outflow		10		160		250
Slangspruit	1040	1200	3400	3300	24 400	9000
Lower Msunduzi	380	330	1600	2500	7800	6400

Camps Drift	550	420	2100	1900	9500	9500

A single sample run was taken at a number of sites in the Camps Drift catchment in order to assess the accuracy of the model simulations. These results are presented in Table 6.3.

Table 6.3. Sampled E.coli concentrations (counts/100ml) with associated modelled values.

Site (description)	Sampled	Modelled
Msunduze downstream of Henley dam	450	250
Msunduze above Mabane stream	800	930
Mabane stream below Sweetwaters	37 000	22 400
Msunduze below Mabane stream	2900	3900
Sinathingi stream at the Msunduze confluence	21 000	12 000 <sup>1</sup>
Msunduze below of Sinathingi stream	2500	5400
Myubikazi stream below KwaMpumuza	14 000	12 700
Msunduze upstream of Ashdown	2500 - 3800 <sup>4</sup>	6900 <sup>2</sup>
Msunduze above KwaPata stream	14 000 - 80004	
KwaPata stream below informal settlement	2300	12 100 <sup>3</sup>
KwaPata stream at Msunduze confluence	8000	•
Stream draining Ashdown	26 000	23 000
Msunduze downstream of Ashdown	7000	7700
Msunduze above Slangspruit confluence	22 000	7800
Wilgefontein stream upstream of Mbali	4487	11 700
Wilgefontein stream in Mbali	440 000 - 550 000 <sup>4</sup>	
Slangspruit stream at Msunduzi confluence	1600	24 400

Key

- The simulated concentration was about 3 km upstream the sample site.
- <sup>2</sup> The simulated concentration was downstream of Edendale, between the two sample sites.
- <sup>3</sup> The simulated concentration was just above Mbali, between these two sample sites.
- <sup>4</sup> Two samples were taken 5 minutes apart, to provide an indication of concentration variability.

The comparison between simulated and observed values is remarkably good, being of the same order of magnitude. This supports the use of the model for ranking the relative contributions from the various sources.

Table 6.4 shows the relative contributions of the various production areas (sources) to the *E.coli* contamination flowing into Camps Drift, as well as an indication of the concentrations in the tributaries and the Msunduze River directly downstream of some of these sources. These estimates enable the ranking of the contributions from different sources and an evaluation of local problems that may not have an impact on Camps Drift itself.

These analyses indicate that the settlements with large populations cause significant contamination during both high and low flows, particularly Sweetwaters, Sinathingi, Edendale and Mbali. But the impacts of Sweetwaters and Sinathingi are partly mitigated by their distance from Camps Drift. Leaking sewers also have a major impact during low flows in both summer and winter. The long-term impact of overflowing sewers during summer high flows is difficult to evaluate, due to their very sporadic nature; although they do not seem to have a significant impact on Camps Drift, they have quite profound local impacts, particularly over shorter time periods. Faecal contamination in the smaller tributaries is serious, due to the potential health implications, but they do not have significant impacts on Camps Drift.

Table 6.4. Relative contribution by source to the *E.coli* load into Camps Drift and an estimate of the median concentrations in the rivers downstream of these sources, during the different flow regimes.

	Source	Source	ontribu	tion (%)	River			<del>-</del>
#	name	winter	low	high		winter	summer low	summer high
0	Henley release	1	2	I	Msunduze	10	150	250
la	KwaMbanjwa	2	3	4	Msunduze	40	350	900
1b	Sweetwaters	9	10	14	Mabane	900	3000	22 500
1c	Smeru	3	4	4	Msunduze	200	1100	4000
2	Sinathingi	11	14	14	Sinathingi	500	2300	12 000
3	Sigodini	2	1	3	Msunduze	300	1500	5500
4	KwaMpumuza	5	3	6	Mvubikazi	600	1300	13 000
5	Edendale	6	5	8	Msunduze	300	1300	7000
6	KwaPata	4	2	3	KwaPata	600	1500	12 000
7a	Mbali	6	7	8				
8	Phayiphini	3	3	4				
9	Ashdown	4	4	4	Msunduzi	400	1600	8000
10	Wilgefontein	5	3	3	Wilgefontein	800	2000	12 000
11	Slangspruit	3	2	5				
7b	Mbali	_12	12	. 15	Slangspruit	1000	3400	24 000
12	Sewer mains	24	25	4				
		100	100	100	Camps Drift	500	2000	9500

This model therefore allows managers not only to focus on the major source areas, but also to assess which activities and sources are contributing most to downstream problems.

#### 6.7 Conclusions

The model presented in this chapter outlined an approach to the identification, ranking and prioritisation of production, delivery and transport of *E coli* in the Camps Drift catchment. It is based on a detailed understanding of the main processes governing faecal contamination of water bodies in a peri-urban catchment, and disaggregates the modelling of these processes as much as possible. This allows managers to identify the actual causes of the problem and to develop detailed management practices to address these (The work presented in this chapter has in fact been used to develop a management plan for the catchment). By separating the production, delivery and transport processes, the model also allows managers to focus limited resources on the most cost-effective solutions, and to identify those production areas, and delivery mechanisms contributing most to the observed water quality problems. This can be used to identify appropriate waste minmisation or waste prevention practices (see Quibell et al 1997). As such this tool primarily supports the selection of appropriate management practices.

However, this model also requires expert knowledge of the processes driving production, delivery and transport of the pollutant in question. Most of the models providing this level of detail also only address one land use and one pollutant at a time(for example the DISA model, which simulates salinity return flow from irrigated fields). They are therefore useful where the priority land use and water quality variables have already been identified, and the manager wants to select appropriate cost effective management practices.

Other similar models are discussed in sections 4G and 4H of the Guide (Pegram and Görgens, 2000).

## 6.8 References

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## 7 CONCLUSIONS

#### 7.1 Introduction

The National Water Act potentially enhances the Department of Water Affairs and Forestry's abilities to manage nonpoint sources. However, the limited resources available to address nonpoint source pollution on a national or even catchment basis, means that managers will increasingly have to focus on sources or processes which contribute most significantly to observed water quality problems.

Table 2.1 outlined a number of nonpoint source assessment needs, which may be summarised as follows:

- What are the important nonpoint source areas?
- What is the relative importance of these areas?
- What are the key nonpoint source activities that contribute most significantly to the observed problems?
- How effective will different management practices be for different controlled activities?

Section 2.3 also outlined the production, delivery, transport and use continuum, which describes the physical processes which lead to nonpoint source pollution. The previous chapters have shown how different models may aggregate or disaggregate these processes, which in turn affects their potential value as management tools. Similarly, different models aggregate or disaggregate land use types, or have different temporal resolutions. These too affect the potential uses of the model.

The nonpoint source assessment tools outlined in the previous chapters represent a range of models aimed at these different management needs. This chapter summarises the contributions made by the different assessment tools to answering these needs, and the model characteristics that affect the use of the modelling tool.

## 7.2 Aggregation and disaggregation in the models

The case studies presented in the previous chapters indicated that models may aggregate or disaggregate certain features, and that this largely affects the use of the models for management purposes. For the purposes of this report the following features of the models are considered;-

- Spatial aggregation (i.e. the lumping of land use types)
- Temporal aggregation (i.e. the time step used in the model)
- Process aggregation (i.e. the lumping of Production, Delivery and Transport)

When land use is lumped, the model can not be used to assess the relative contributions of different land use types. This limits the use of the model to variables where it is clear which land use is causing the problem, or where the manager may only be interested in total nonpoint source contributions from the catchment. Land use lumped models are, however, easier to calibrate and do not need a detailed understanding of nonpoint source processes.

When models are temporally lumped (i.e. steady state or no time step) they can not be used for scenario planning, or to assess the effects of future land use changes, or water resource use options. This affects their use to generate nonpoint source loads for other models.

As indicated in Chapter 2, management of pollutant production, delivery or transport can be equated to management philosophies of waste prevention, waste minimisation and impact minimisation

respectively. Models that lump these processes, therefore, limit their use to select management practices aimed at these philosophies.

The following section highlights the attributes of the models presented in the previous chapters, and how these affect their use for nonpoint source management.

## 7.3 Model attributes that support different management needs

The GIS based modelling tool (Chapter 3)

This method provided a rapid screening and scoping tool, which identifies potential nonpoint source areas in relatively large catchments on a qualitative basis. As such it provides answers to "What are the important nonpoint source areas?" It has the advantage of providing a map of potential nonpoint source production areas, and can easily be adapted to answer more specific management needs.

The model has the following attributes: -

Attribute	Description
Land use	Very disaggregated - models 20 land use types on a qualitative basis
Time scale	Has no time scale and only indicates potential pollutant production
	areas
PDT <sup>1</sup>	Only models potential production

1 This refers to Production, Delivery and Transport processes

This means that the model can provide a high level of detail on the relative contributions of different land use types. For example which land use types are most often associated with high potential pollutant production. Similarly, the model can estimate the percentage of any area which has high medium and low pollutant production potential. However, as the model is qualitative only, it can not be used for direct comparisons.

Simple statistical and deterministic models (Chapter 4)

These models have the advantage of providing quantitative assessments, and can therefore contribute to prioritising nonpoint sources in different catchments. However, the models are based on pollutant export, and therefore are restricted to modelling loads from gauged catchments. As such the model answers the question: "What is the relative importance of different sub-catchments?".

The models have the following attributes:-

Attribute	Description
Land use	Statistical models lump all the land use in the catchments. PEM disaggregates only in terms of sediment production.
Time scale	Time scale very variable potentially hourly to monthly.
PDT	Only model export from the catchment

1 This refers to Production, Delivery and Transport processes

This means that the models are restricted to gauged catchments, and can not be used to select management practices. They are best used were the catchment is relatively homogenous, and were nonpoint source loads may be required as input to other models.

## The CWM (Chapter 5)

This model supports the next level in the management decision hierarchy. This model associates a range of nonpoint source activities with their pollutant washoff potential. However, the model requires an expert understanding of the factors causing nonpoint source pollution, such that appropriate washoff functions can be used. The model has the advantage that it is not (or should not be) calibrated, and that it can allow the manager to compare the relative loadings from different land use activities. As such the model supports a prioritisation level of assessment, and answers the

question: "What are the key nonpoint source activities that contribute most significantly to the observed problems?"

The model has the following attributes:-

Attribute	Description
Land use	Disaggregated - models 10 land use types on a quantitative basis
Time scale	Monthly to fit in with systems analysis modelling
PDT <sup>1</sup>	Groups Production and Delivery

<sup>1</sup> This refers to Production, Delivery and Transport processes

This model provides very valuable data on the relative contributions from different nonpoint source types, but as it does not model the detailed processes of production and delivery it can not support the selection of management practices.

## The Faecal Coliform model (Chapter 6)

This model is based on a detailed understanding and modelling of the processes that lead to pollution. This means that the effects of different activities, as well as the fate of the pollutant once it has reached the water resource, can be modelled. This means that the model can support the selection of different management practices, and supports the question: "How effective will different management practices be for different controlled activities?". However, its disadvantage is that it requires a detailed understanding of the factors that cause nonpoint source pollution.

The model has the following attributes:-

Attribute	Description
Land use	Only one land use and one variable
Time scale	Variable time scale
PDT <sup>1</sup>	Separates Production, Delivery and Transport

<sup>1</sup> This refers to Production, Delivery and Transport processes

This model (and other similar models) only addresses one land use type, and one variable. They are therefore best used were it is clear where the pollutants originate. However, they provide detailed modelling of the production delivery and transport mechanisms, and as such support the selection of nonpoint source management practices.

### 7.4 Conclusions

None of the nonpoint source tools investigated here have is devoid of value to water quality managers. However, the range in management decision needs requires a range in nonpoint source assessment tools. As such it is not practical to suggest any one generic tool for managers, or to "panelbeat" a particular tool to fit a particular management need. More importantly, this country cannot afford to undertake detailed and costly modelling studies which do not meet management needs, or which provide more than is needed to address the immediate problem.

Water quality managers and modellers should, therefore, carefully match the model capabilities with management needs. In this respect nonpoint source assessment should begin with the identification of the manager's needs. Water quality modellers should then interpret these needs in terms of the models characteristics with respect to the aggregation and disaggregation of model parameters or of the Production, Delivery, and Transport processes.

This report has illustrated how different modelling approaches can support nonpoint source management needs, and hence how model aggregation and disaggregation affects the use of the model. The Nonpoint Source Assessment Guide provides further guidance with respect to the selection of the most appropriate nonpoint source assessment tools.

## Other related WRC reports available:

## Policy considerations for nonpoint source management in South Africa

GC Pegram · AHM Görgens · GE Quibell

Classification of nonpoint sources is required for legal purposes, because the appropriate management approach varies for different nonpoint source types. Although all human activity potentially has an impact on the receiving water environment, cost-effective nonpoint source management requires the prioritisation of those activities with the greatest impact. Therefore, a simple classification system is required to enable and focus nonpoint source control and enforcement. "Cutoff levels" should define the intensity or size of these activities, above which nonpoint source management is required, based on the potential impact on the receiving water environment.

 Classification of nonpoint sources should be based on source type (land use activity), with cutoff levels reflecting the size and intensity of the activity which has a potential impact on the receiving water environment.

The listing of those activities which are classified above the "cutoff levels", should be enabled through the water act, as the basis for nonpoint source management. Regulations for control and enforcement should be specified according to these classes (i.e. listed activities).

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